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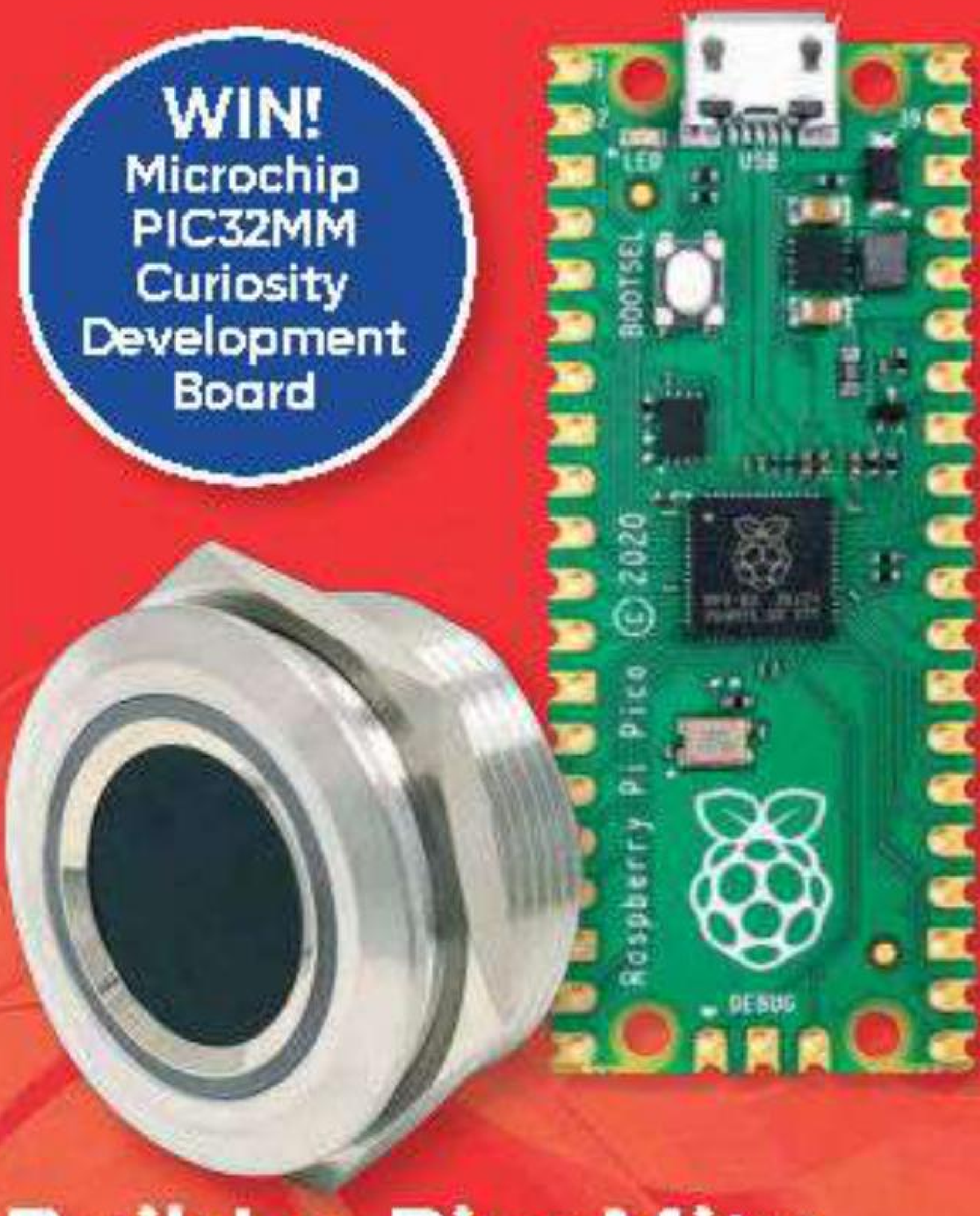
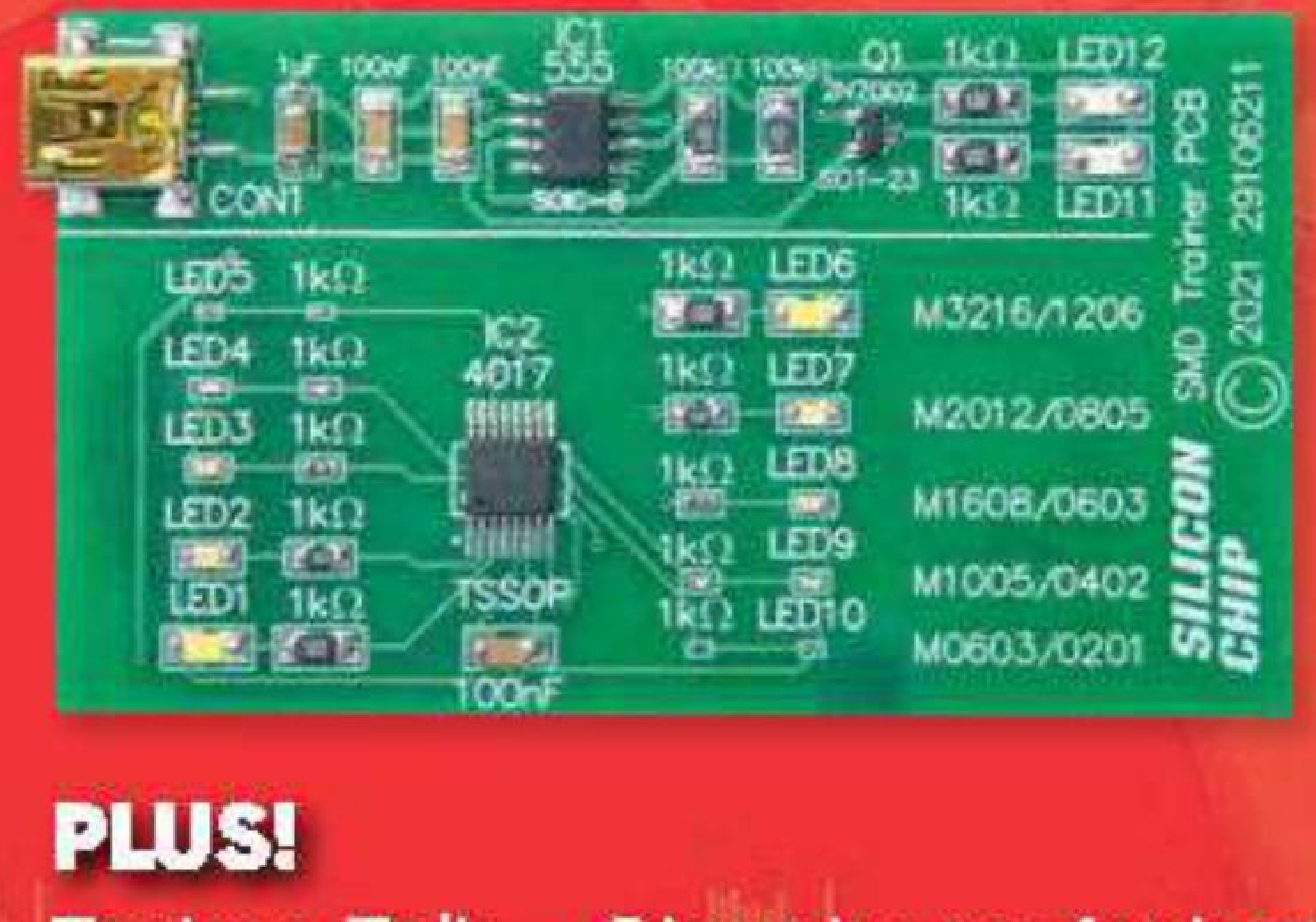


Build a PicoMite fingerprint reader

SMD Trainer board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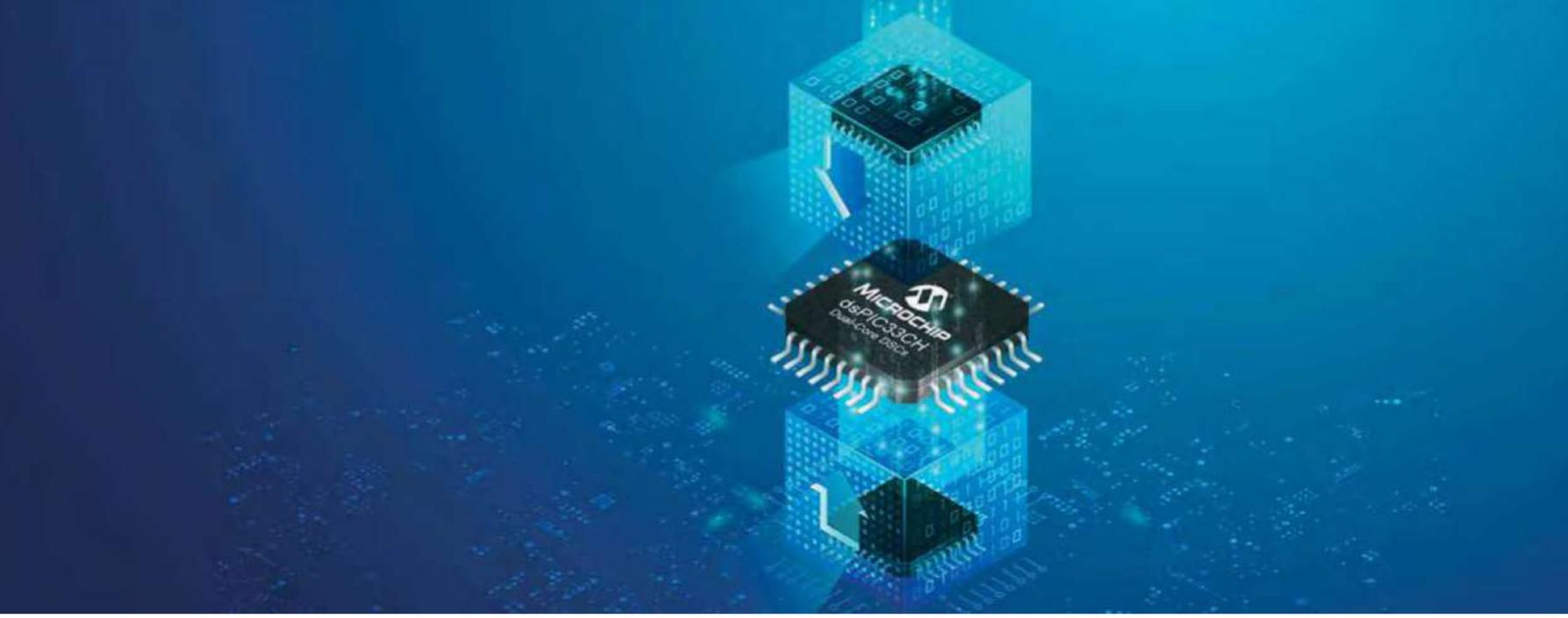

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Practical
Electronics

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The January 2023 issue of *Practical Electronics* will be published on Thursday, 1 December 2022 – see page 72.

WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

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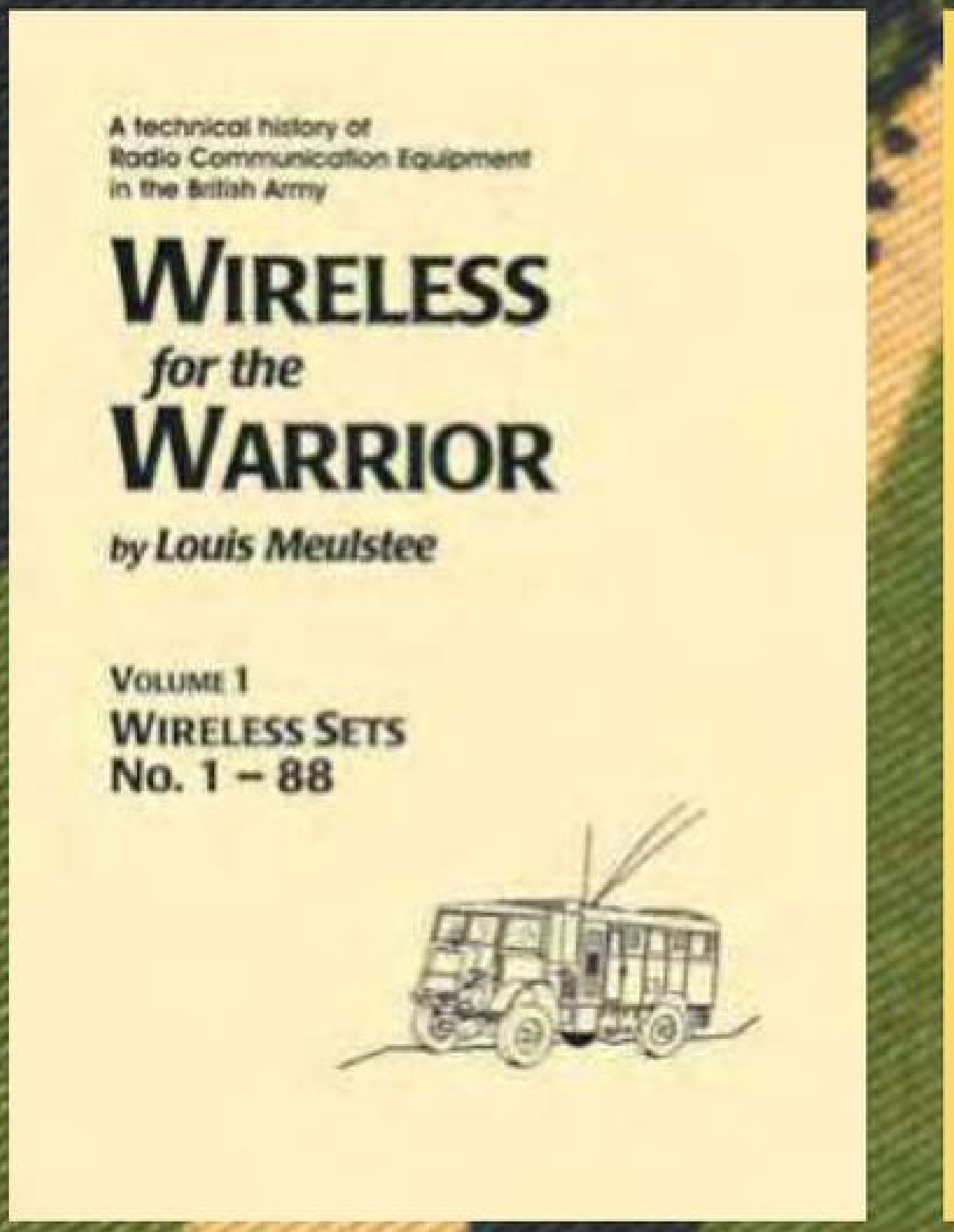
Volume 3 covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.

Volume 4 covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.



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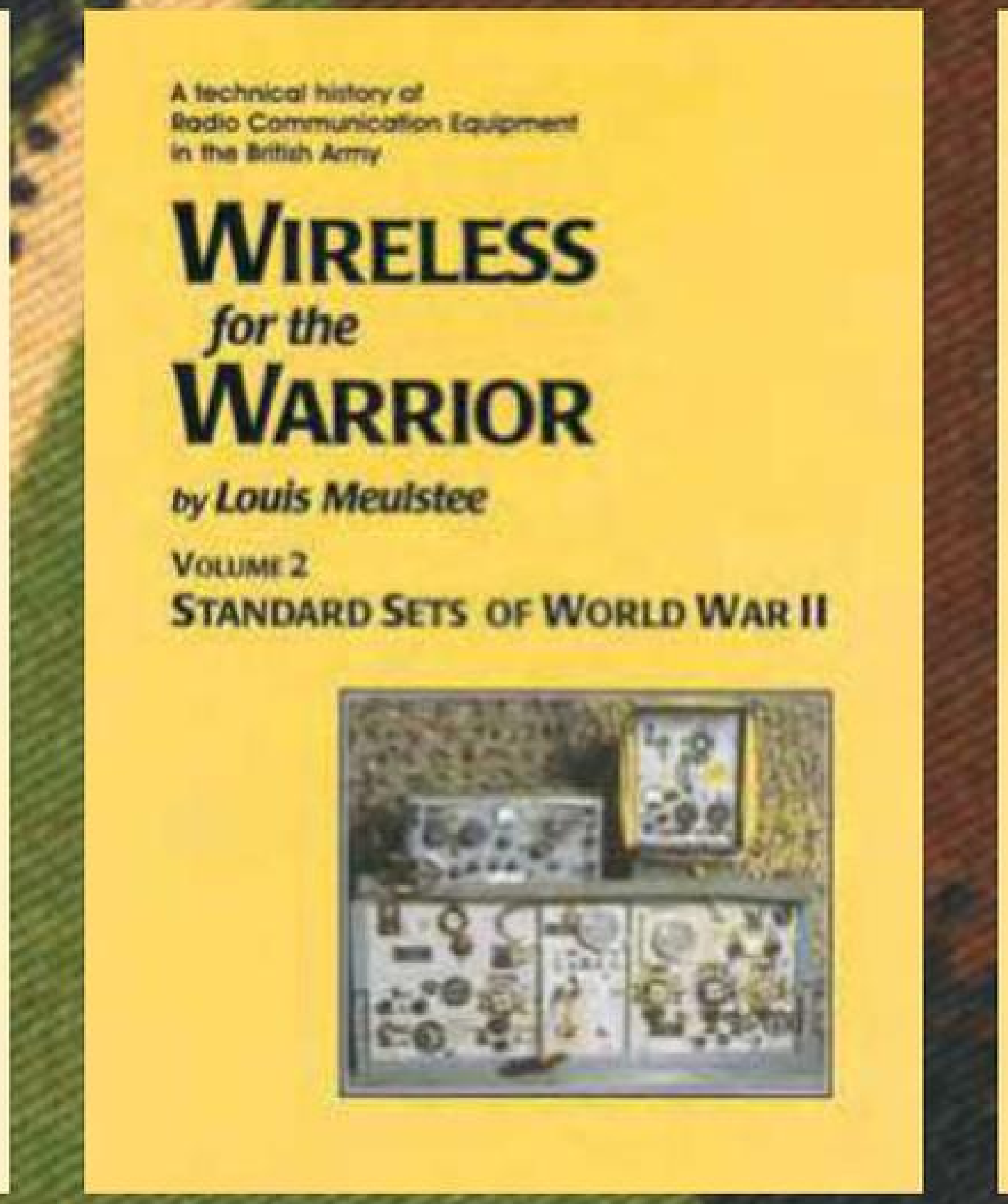

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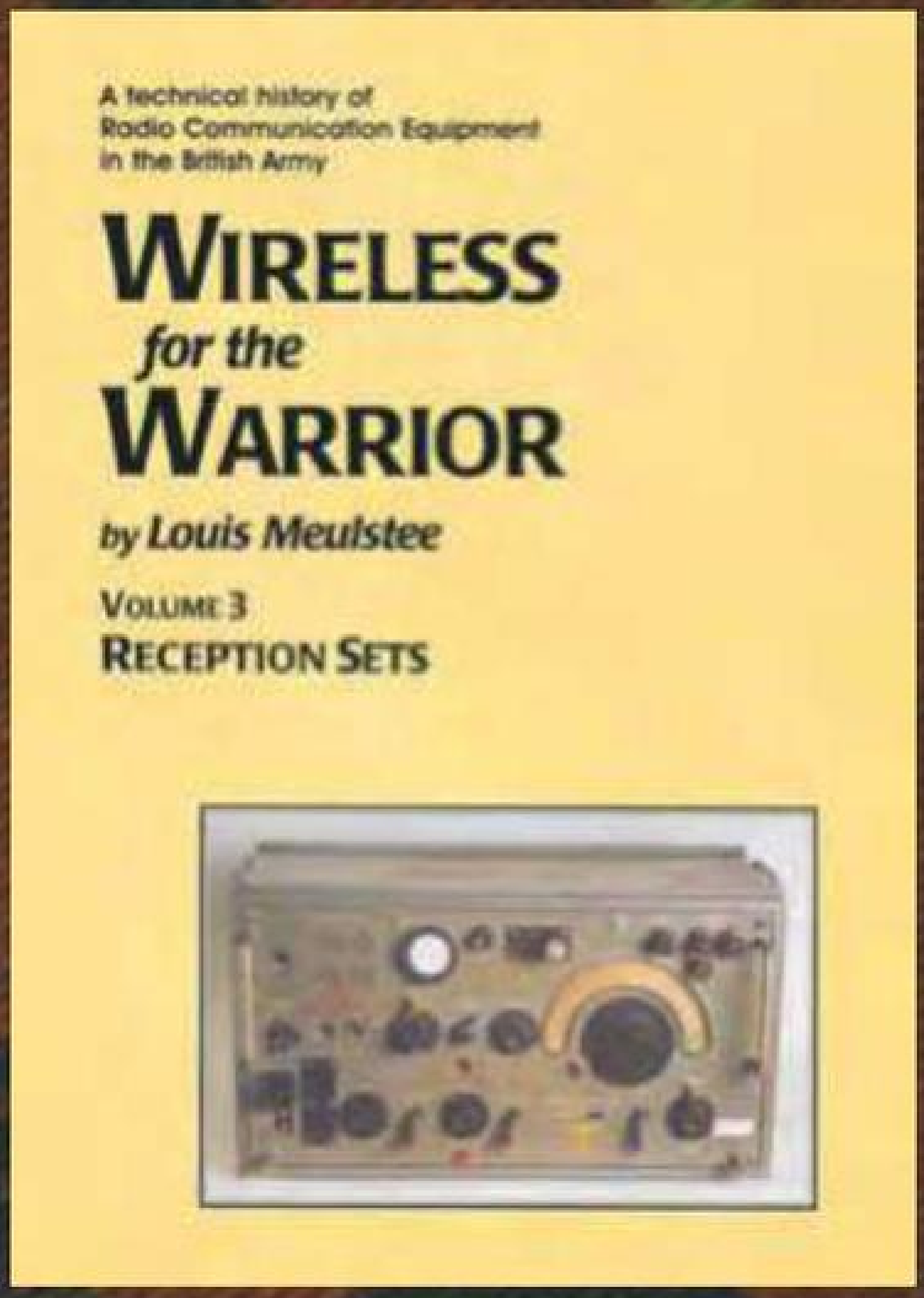

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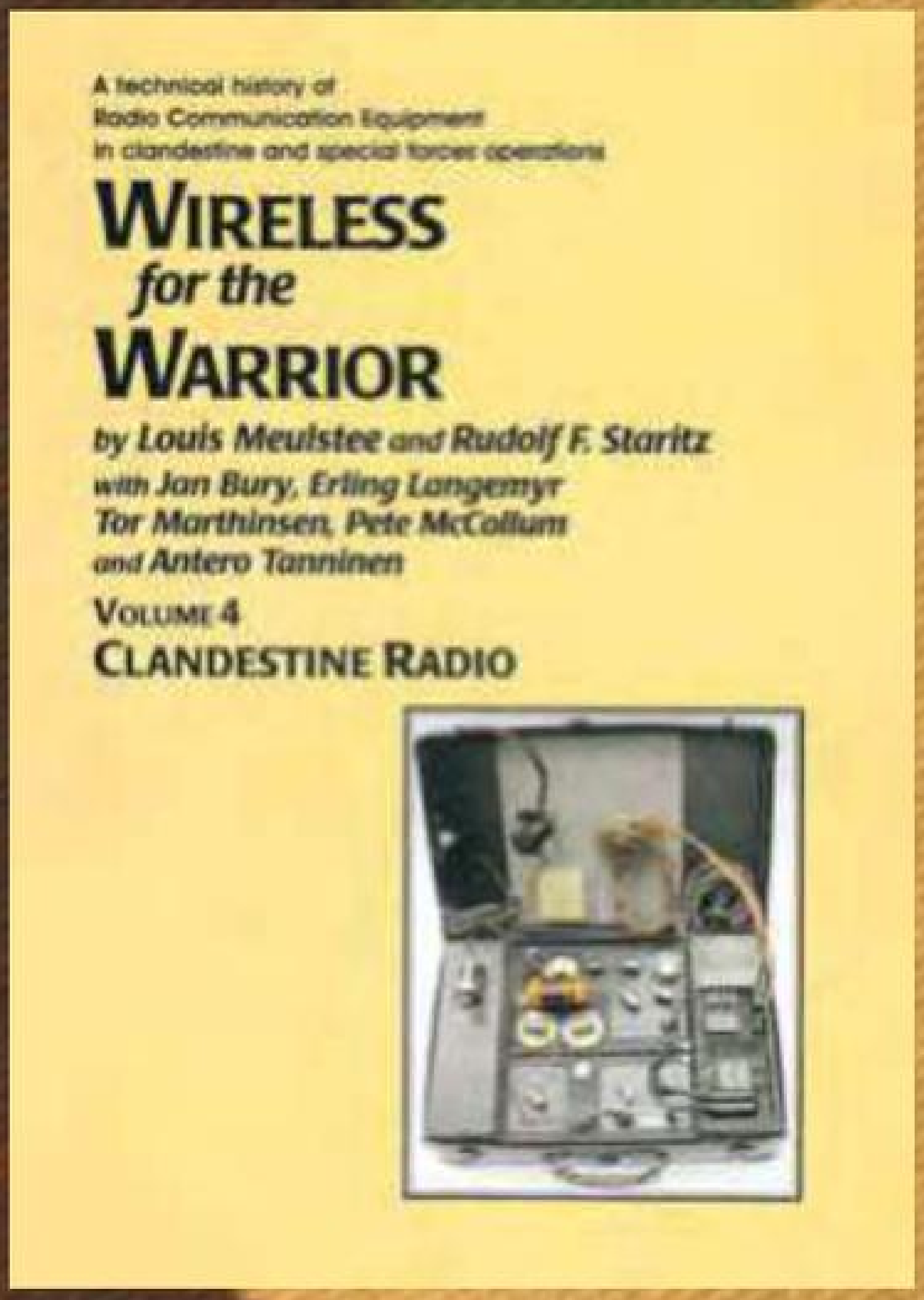

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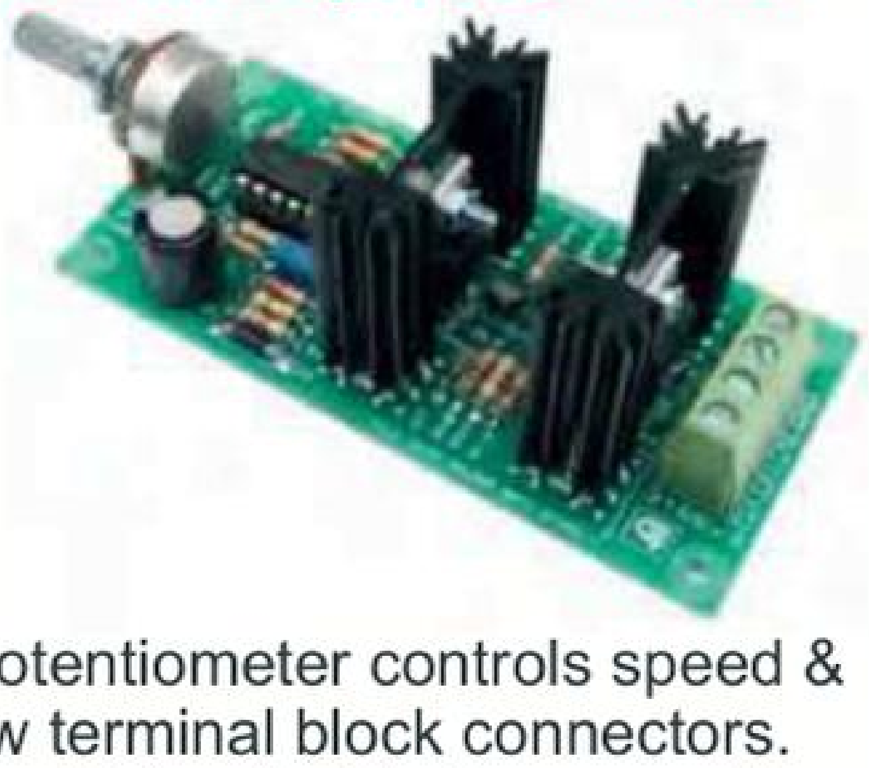

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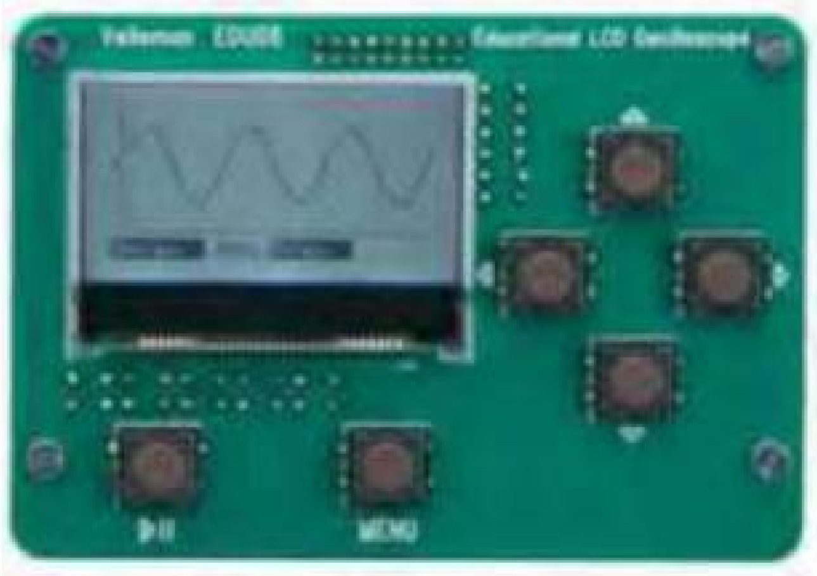

Build your own LCD oscilloscope with this exciting new kit. Learn how to read signals. See the electronic signals you learn about displayed on your own LCD oscilloscope. Despite the low cost, this oscilloscope kit has a lot of features found on expensive units like signal markers, frequency, dB, true RMS readouts and more. A powerful auto-setup function will get you going in a flash!
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All reasonable precautions are taken to ensure that the advice and data given to readers is reliable. We cannot, however, guarantee it and we cannot accept legal responsibility for it.

A number of projects and circuits published in *Practical Electronics* employ voltages that can be lethal. You should not build, test, modify or renovate any item of mains-powered equipment unless you fully understand the safety aspects involved and you use an RCD (GFCI) adaptor.

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Soldering surface-mount devices

Apart from the general shortage of silicon over the last few years, one of the biggest gripes for amateurs and hobbyists has been the inexorable rise of SMDs (surface-mount devices). While these are fantastic for mass producing compact, cheap electronic products, for the home design/constructor they can be a real problem.

The simple fact of the matter is that soldering SMDs is inherently harder than ‘traditional’ through-hole components. First, there are no ‘legs’, wires or holes to secure and orient parts before applying solder – components just sit on the board. Second, and probably here is the biggest problem, SMD parts are smaller, sometimes considerably smaller than their through-hole counterparts. In fact, some parts are so small they are barely visible and are specifically designed to be applied using automated pick-and-place machines, making the challenge of manually placing and soldering these minute parts almost impossible.

Unsurprisingly, since commercial and industrial consumers of silicon prefer the lower costs involved with SMD-based production, the market has simply followed demand, and for some years we have been in the situation where certain new ICs are not even supplied in through-hole format – strictly SMD.

So, what to do? Well, there are two options. It’s worth remembering that despite all of the above, there are still very many through-hole components available, and while you would be limiting some of your options by avoiding SMDs, there is still enough user-friendly through-hole silicon to keep most people happy. If you want to stick to just through-hole then you can. That said, however, a better option is to grasp this nettle and learn to solder SMDs. If that’s your preferred route then you’re in luck, because this month we have a great article and a trainer project to help you learn to solder SMDs. Do remember that not all SMDs are the same size. While some are definitely out of reach for manual solderers, plenty of SMDs are entirely useable with a bit of practice and some useful guidance. You may need to invest in a new soldering iron, plus a few other tools and materials, but the cost is not high and the rewards justify the outlay.

If you’ve been meaning to take the plunge into the SMD pool, now is the time jump in!

.

Matt Pulzer
Publisher

Giant Boost for Batteries

Techno Talk

Mark Nelson

Imagine a battery that you can recharge a thousand-times faster than anything available today. If you can't, you should read this article. It covers the intriguing possibility of quantum super-batteries that can recharge in minutes or even seconds.

When the BBC began to broadcast 100 years ago, it was clear that the crude 'crystal set' receivers offered for sale were hardly what you would call a mature technology. Wearing headphones and poking around to find the most sensitive spot on the crystal wasn't a user-friendly way of listening to the wireless, and it took a while before valve radios gave us straightforward tuning and easily adjustable volume controls.

In the same way, it's hard to deny that in some ways the rechargeable batteries installed in road vehicles are also unwieldy and inefficient. Lithium-ion batteries may be adequate for computers and smartphones, but when scaled up for motive power applications, they are clearly bulky, weighty, slow to recharge and potentially unsafe. The lithium and other 'critical minerals' used to manufacture them are not only far from plentiful, but also vulnerable to being weaponised in global trade wars. What we desperately need is a radically different battery technology that is easier to make, with far less ecological impact, faster to recharge and offering much greater energy density within a given physical volume.

Bring on the super cell!

Does this perfect battery technology exist? Conceptually it does, and scientists around the world are doing their utmost to bring it into a state of reality. It goes by the name of the 'quantum battery' and if the term 'quantum' is a word that you recognise but know little about, don't worry – you're in good company. However, so you don't need a degree in physics or higher maths to understand this article – there's a brief explainer panel at the end.

So, how do quantum batteries differ from the batteries used in smartphones and electric vehicles (EVs)? To quote the website **scitechdaily.com**, quantum batteries are a new class of energy storage devices that operate according to the principles of quantum physics, the science that studies the atomically small, where the laws of classical physics do not always apply. Remarkably, it is possible to create a type of quantum battery in which the recharge time is related inversely to the amount of stored energy.

A demonstration battery of this kind has now been built by a team of researchers in Italy led by Tersilla Virgili and Giulio Cerullo. They write: 'This leads to the intriguing idea that the charging power of quantum batteries is super-extensive, meaning that it increases faster with battery size. Each molecule represents a unit that can exist in a quantum superposition state of two energy levels (fundamental and excited), similar to the way a qubit, the basic unit of quantum information, can be both 0 and 1 simultaneously in quantum computers.'

Collective behaviour makes for strength in numbers

Our two experts continue: 'By constructing the quantum battery in a way that units can exist in superposition, the total system can behave collectively. This behaviour, known as 'quantum coherence', allows the units to act cooperatively [interconnectedly], giving rise to a hyper-fast charge that depends on the number of molecule-units. In the future, this type of device can be applied in various scientific and technological fields, such as wireless chargers, solar cells and cameras.'

This hyper-fast speed points immediately to the killer application of quantum batteries: the ability to slash the time taken to recharge the batteries of EVs. The $64,000 question is, by how much? Researcher Ju-Yeon Gyhm at the Institute of Basic Science in the Republic of Korea has calculated that quantum batteries could be charged in a thousandth of the time that classic batteries would take to be revitalised. What's more, in normal batteries, the power increases with the number of cells in parallel. But in quantum batteries, you can make the power increase with the *square* of the number of cells.

Highly speculative

Rather as Schrödinger's cat (see below) can be simultaneously both alive and dead, the prospect of quantum batteries becoming viable for practical, commercial application is both real and unreal. Dr Kavan Modi, associate professor of quantum physics at Monash University (Australia) concedes: 'For us, the theory [is] just an interesting playground to explore fundamental ideas of time and energy. I don't think there will be technological applications. Of course, I may be completely wrong.'

He may be. If you consider quantum computers, these were once purely conceptual but are now close to becoming a commercial reality. Google aims to have a commercial-grade quantum computer by 2029, and is only one of several companies racing to build a business around this emerging technology. In the same way, the overwhelming economic necessity to find a means of recharging EV batteries as rapidly as filling a petrol tank will incentivise research and development of viable quantum batteries.

At this stage, the only certainty is that nobody can say whether or when quantum batteries will be commercialised. But consider LED lighting: electronically generated light was demonstrated as long ago as 1907 by the English experimenter HJ Round of Marconi laboratories, using a crystal of silicon carbide and a cat's-whisker detector. It took more than a century to produce affordable LED lamp bulbs!

Quantum magic

A qubit (short for 'quantum bit') is a basic unit of quantum information, used in quantum computing. In conventional computing the unit is a bit (short for binary digit), which can have only one of two states: one or zero. But in quantum systems, a qubit can exist in both states simultaneously, a property that is fundamental to quantum mechanics (and quantum computing). The classic example of this is Schrödinger's hapless cat, which hypothetically can be simultaneously both alive and dead, as a result of its fate being linked to a random subatomic event that may or may not occur. **https://bit.ly/pe-dec22-cat**

Win a Microchip PIC32MM Curiosity Development Board

Practical Electronics is offering its readers the chance to win a Microchip PIC32MM Curiosity Development Board (DM320101) – and even if you don't win, receive a 15%-off voucher, plus free shipping for one of these products.

The PIC32MM Curiosity Development Board features the new eXtreme Low Power (XLP), PIC32MM 'GPL' family (PIC32MM0064GPL036) of low-cost microcontrollers. This board is a simple and easy-to-use platform that facilitates quick PIC32MM evaluation, experimentation and application prototyping. The board also includes an integrated programmer/debugger and offers seamless integration with Microchip's MPLAB X IDE and MPLAB Code Configurator for easy set-up and development.

This PIC32MM family features core-independent peripherals, designed to offload the CPU, such as Configurable Logic Cells (CLC) and Multiple-output Capture Compare PWMs (MCCPs) which help enable sensorless BLDC motor control applications. The devices achieve a 79 CoreMark score at 25MHz operation, featuring the compact microMIPS instructions, microAptiv UC core and a shadow register set for fast interrupt context switching. The microMIPS ISA combines 16-bit and 32-bit instructions for compact code size.

Owing to its low-power, low-cost and expansion capabilities, the PIC32MM Curiosity Development Board is ideal for developing battery-operated applications, portable medical monitoring devices and IoT sensor nodes.

The board also offers various user interfaces like switches, LEDs and potentiometer, and supports a MikroElektronika mikroBUS interface that lets you tap into an ecosystem of over 300+ add-on click boards enabling, customers to accelerate application prototype development. Additionally, Bluetooth Low Energy communication can easily be added using Microchip's BM71 module footprint.

Worth $34.00 (approx £30.00) each

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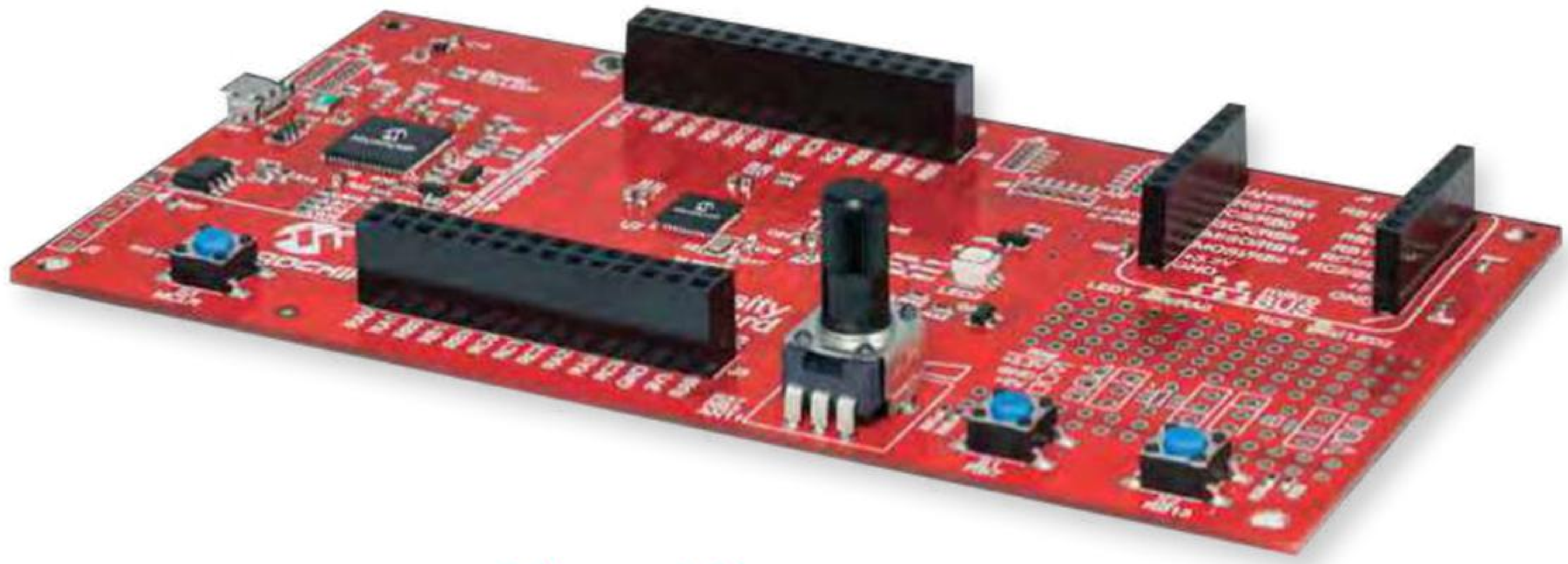
Microchip PIC32MM Curiosity Development Board



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The closing date for this offer is 30 November 2022

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Julian Grota

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The **Fox** *Report*

Barry Fox's technology column

From virtual reality to virtue signalling

IAAPA, the self-styled 'Global Association for the Attractions Industry' (don't ask me how the acronym derives), recently came to the ExCel Conference Centre in Docklands near London City Airport. (See: **www.iaapa.org/expos/iaapa-expo-europe** for more details.)

Founded in 1918, IAAPA is – in plainer English – the trade body for companies involved in the big business behind the world's amusement parks, theme parks, attractions, water parks, resorts, family entertainment centres, zoos, aquariums, science centres, museums, cruise lines, manufacturers and their suppliers.

ExCel is a huge cluster of giant, utilitarian exhibition halls, now nicely accessible by the new Elizabeth tube line as well as the driverless Docklands Light Railway.

If you've ever watched the movie, *The Long Good Friday*, the transformed ex-docks area round ExCel is what Bob Hoskins cleverly foresaw before he was scarily disappeared in the back of a cab.

I went along looking for new electronic technology that might make a day at a 'park' more fun… or more scary.

What I came away with was an overriding impression, best summed up by a bunch of pictures. In a nutshell, the Attractions industry sees the next big thing as virtual reality (VR) and augmented reality (AR). Although only a few couch potatoes will don headsets to watch movies (which is what so absolutely predictably kills 3DTV and cinema 3D every time it is re-invented) people who go to theme parks may well be up for wearing one.

Put simply, the theme park industry is over-layering VR/AR tech on conventional park rides, games and experiences – see the pictures below. Most speak for themselves, except the one which shows the tribute to the Queen – who had just died – electronically plastered all over ExCel's front entrance. What a pity no-one

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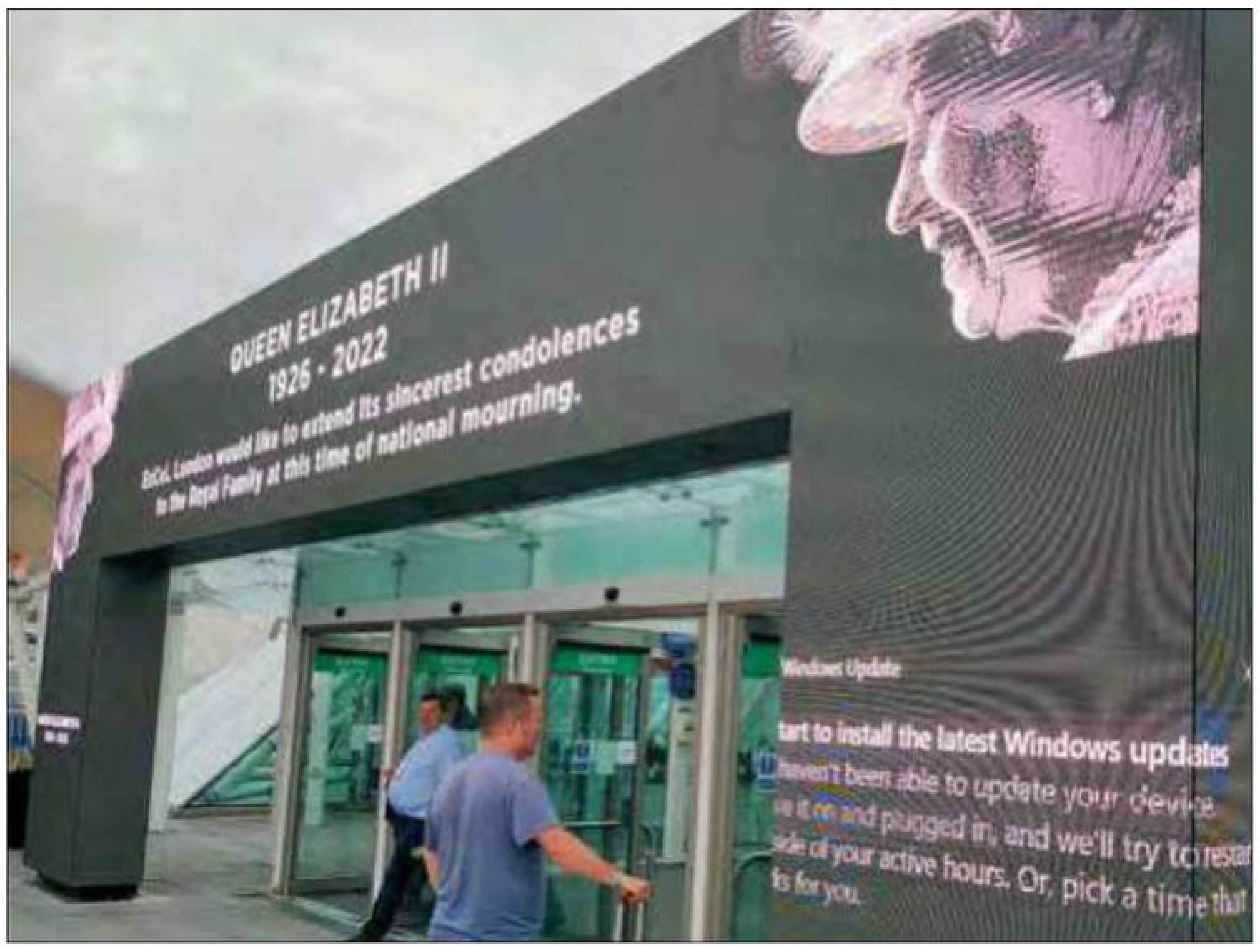
QUEEN ELIZABETH II
1926 - 2022
ExCeL London would like to extend its sincerest condolences to the Royal Family at this time of national mourning.
Windows Update
tart to install the latest Windows updates
haven't been able to update your device
ve it on and plugged in, and we'll try to restar
side of your active hours. Or, pick a time that
ks for you.

on ExCel's tech staff seemed to have noticed that the Windows PC used to source the image had downloaded itself an operating system update and was begging for a re-start.

Online 'safety'

The UK will be one of the first countries in the world to pass laws aimed at making online users safer, while preserving freedom of expression. The Online Safety Bill – due 2023 – will introduce rules for sites and apps such as social media, search engines and messaging platforms, along with pretty much every service used to share content online.

Few people will argue with the basic idea and good intention, providing it is handled well. So, who will handle it?

A safe pair of hands?

Ofcom has the gig, and says it will, 'within the first 100 days,' have a draft *Code of Practice* for the industry and then 'consult publicly' ahead of going live in 2024. Ofcom will have 'a range of investigation and enforcement powers', 'build on the expertise we have already brought in from the technology industry', 'work with other regulators… to ensure a joined-up approach' and 'ensure the tech companies are more transparent and can be held to account for their actions.'

Says Ofcom: 'The Bill does not give Ofcom powers to moderate or respond to individual's complaints about individual pieces of content…the sheer volume of online content would make that impractical.'

Fair enough, but it means Ofcom will have to rely on unspecified other bodies to steer enforcement. This is exactly the way it works for controlling telecoms service providers; or, frankly, doesn't work.

As I put on record in *Practical Electronics* in October 2022, Ofcom's consumer complaints process is a pantomime farce which can trap anyone daring to complain about a telecoms service provider in a circular loop – with Ofcom refusing to accept individual complaints and referring people to the Telecoms Ombudsman and Information Commissioner (ICO), while the Ombudsman refers complaints back to Ofcom and to the ICO, while the ICO refers people back to the Ombudsman; and all the while Ofcom boasts that the number of complaints is falling, as people doubtless just get weary of life and give up on complaining.

Just for the heck of it, I sent Dame Melanie Dawes, Ofcom's Chief Executive, a personally addressed letter, suggesting that if she were interested in the way Ofcom's own guide literature is muddled and how real-world complaints can get loop-locked, I would show her some carefully documented examples.

My letter mysteriously failed to reach her office. Ofcom then asked for a resend but failed to provide a direct email address for her office or personal assistant. So, fool that I am, I travelled to London and hand-delivered a copy to Ofcom's HQ in Southwark, along with hard copy of the *PE* article.

I've heard nothing from Dame Dawes, but a member of the Ofcom's Consumer Contact Team has been delegated to recommend seeking independent legal advice and using Ofcom's complaints system to complain about Ofcom.

They just don't get it, do they? And it surely hangs a question mark over how Ofcom will now handle the extra task of controlling Online Safety.

…and finally

I collect examples of how official bodies are often run by officials who clearly do not use the IT they are expecting consumers to use – or have utter contempt for consumers.

The latest, and one of the best yet examples, is to be found on Camden Council's Planning Search site. I suggest you look quickly before they finally wake up to the absurdity of the search process, which has so far obstructed anyone trying to trace a planning application for a building, by not unreasonably expecting it to show up under its street address, see: **https://bit.ly/pe-dec22-daft**

Note the instruction that to search by site address, 'you can enter a house number and street name or post code'. So far, so good. But you also need to know that the 'Site address is sensitive to punctuation and spaces. Do not use commas or the word London.'

Hmmm. Not very user-friendly. But let it pass. But here's the killer-driller: if you want to get a result from your search you must, 'use % when typing addresses; eg, %1%Camden%Road%.'

Discovering this Boolean obstacle to essential everyday planning business makes yet another of those 'couldn't make it up' moments.

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Net Work

Alan Winstanley

This month's Net Work focuses on some energy-saving and monitoring resources, as well as looking ahead to the future of nuclear fusion.

It was exactly three years ago, in the December 2019 issue, that I wrote about the rocky roll-out of Britain's smart meter programme. Smart meters originated as an EU policy, and I described how, a decade earlier, the EU's energy policy had established three fundamental goals: to secure energy supply, to combat climate change and to establish an 'internal market'. As part of these lofty ambitions, 80% of traditional electricity meters would be replaced with 'smart' ones by the year 2020, or so the EU Commission hoped.

With energy supplies now in turmoil, radical measures have been introduced across Europe to reduce consumption, shore up gas reserves and import more liquefied natural gas (LNG). German public buildings and swimming pools, for example, have reduced their heating (or turned it off altogether) and unnecessary amenity and advertising lighting has been turned off, with more cutbacks to come.

At the time of writing, the UK is currently exporting some 2.2GW of electricity through its interconnects to Europe, while importing 1.1GW from Norway at the same time. As mentioned last month, the Gridwatch website **www.gridwatch.co.uk** gives a very useful summary of Britain's energy production and usage – but remember it's for guidance only.

Winter of discontent

The ongoing stability and resilience of energy supplies are probably foremost in everyone's minds. Unprecedented price increases have started to hit consumers and that's before the winter weather draws in, when demand for energy will soar and supplies will be stretched. While UK consumers are now receiving Government energy subsidies until April 2023, everyone is being encouraged to start saving energy, and in last month's *Net Work* I suggested that consumers might receive some sort of 'carrot' from electricity suppliers to reduce peak-time electricity consumption. It now seems likely that cash incentives may be offered to help shift energy consumption to off-peak periods.

The National Grid holds the UK's supply lines together, and it spells out the picture for the National Transmission System (the gas network) in its *Gas Winter Outlook 2022/23* at: **https://ngrid.com/3z9BpA9** (PDF, 51pp); the winter forecast for electricity is published at: **https://bit.ly/3CULty6** (PDF, 25pp).

These publications are aimed mostly at industry, so readers will probably find the website of National Grid ESO more enlightening (see: **www.nationalgrideso.com**). The Electricity System Operator manages all of Great Britain's electricity supplies, and with it comes the job of balancing the nation's energy supply and demand. Their own annual *Winter Outlook* heralds some 'cautious action' that will be taken to secure wintertime supplies (see: **https://tinyurl.com/2ee2bz4f**). Under the heading *New times requires new tools*, one of the ESO's new objectives is 'Creating a new "Demand Flexibility Service" where energy users will be incentivized to reduce consumption/turn off power at key times to reduce overall demand across the system', as they put it.

This new 'demand management tool' could pay consumers *not* to consume electricity. Unconfirmed reports suggest that inducements would start at a minimum of £10 for using energy off peak. Using washing machines and dishwashers, EV chargers and other current-heavy appliances this way could shave 2GW off the nation's peak electricity consumption, the ESO hopes.

Presently, there's nothing to suggest that consumers would be penalised for using energy at peak times. Their contracted tariffs would presumably prevail, leaving users no worse off financially. I've also suggested in the past that smart meter owners might start to receive a text message or a nag-screen popping up on their IHD (In-Home Display) when demand is high, encouraging them to turn down the lights. If you don't have a smart meter, then you won't get the message, and presumably you will miss out on any cash bonus they offer.

Killer watts

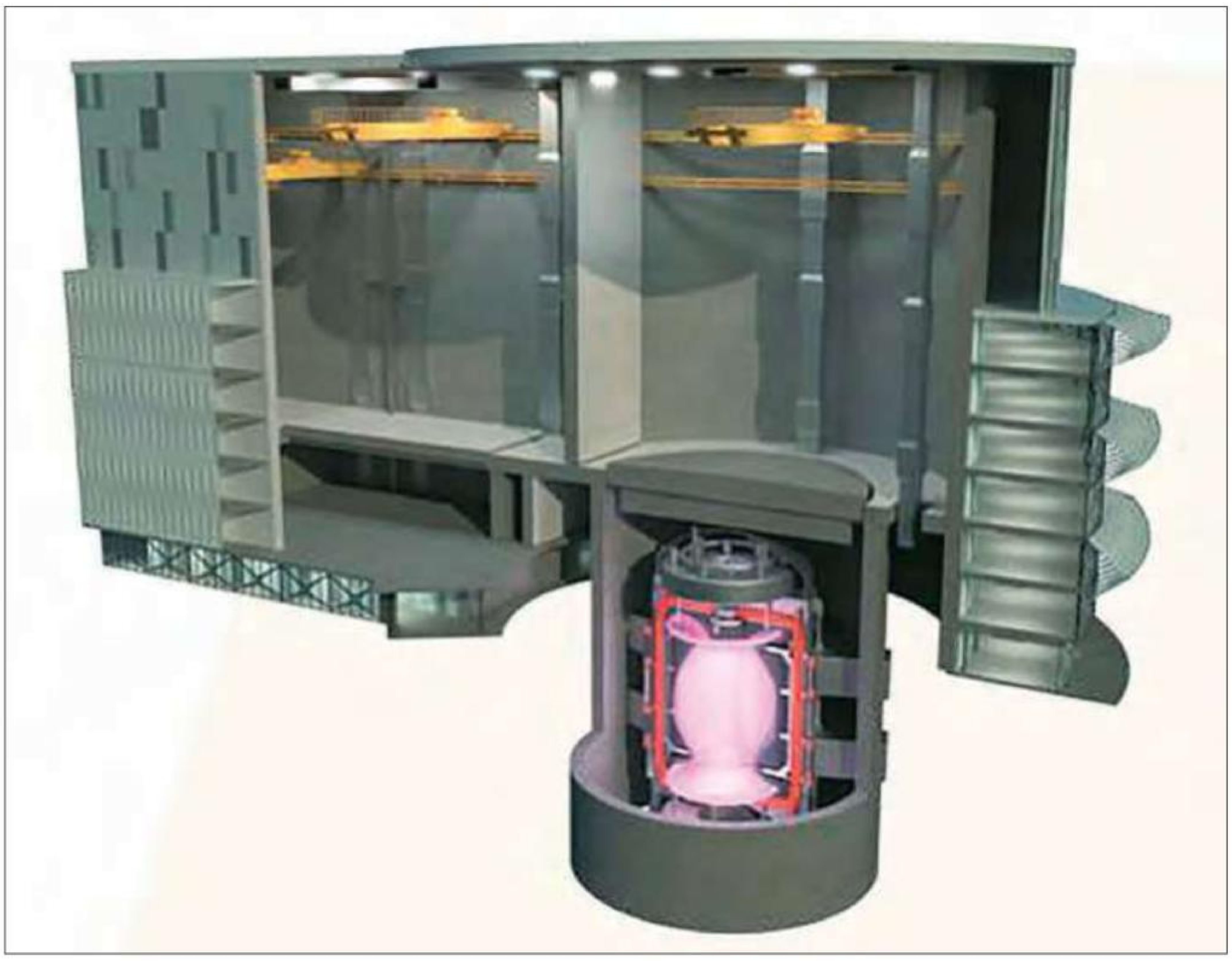
A clear trend is emerging of consumers fixating on their smart meters or IHDs, LCD monitoring devices that glow red in anger when major appliances are devouring power. One family friend goes out of her way to keep her smart meter 'in the green' and feels put under intense pressure when the cooker's turned on; likewise, I read how one Amazon reviewer exclaimed that a portable dehumidifier 'takes hardly any electricity and my smart meter stays on green when this is working'.

It's obviously no bad thing if IHDs influence energy consumption this way. There are also smartphone apps available that will work in conjunction with your smart meter data, or they can work in lieu of an IHD – useful if your supplier has yet to provide an IHD or

The Loop 'Smarter Meter' app displays your smart meter data on your smartphone or tablet, and can help optimise energy consumption.

yours has been lost or damaged. One example is the Loop 'Smarter Meter' app. Loop claims it helps you understand your electricity usage and shows you easy ways to use less and save money. Also, they claim as much as 30% of a total bill can be due to phantom loads running in the background (think of it as a household's quiescent current) – Loop will help to identify and eliminate them. Loop reckons users cut their usage by 10% on average, and the app will also simplify the job of changing supplier (because in the UK, consumers aren't tied to a local energy utility company and can pick their own supplier). The app is free from your mobile platform app store; see **https://loop.homes** for details. I tried to find out more about the app's technical workings, but Loop was unreachable by email, and there is no phone number either. The name behind Loop, Trust Power Ltd, seemed unapproachable too.

PE readers will know that a kWh rating relates to kilowatts drawn per hour, and calculating an appliance's running costs is simple enough, though the unwelcome addition of gas and electricity 'standing charges' adds some £270 per year to our bills. These are the kind of calculations we will soon all be making, and a handy online Electricity Cost Calculator at **https://bit.ly/pe-dec22-ecc** includes tariffs for all major countries and gives the total cost of electricity consumed over a set period in minutes or hours. (For UK readers, information about the current 'price cap' will be found on Ofgem's website at: **https://bit.ly/pe-dec22-cap**). Unfortunately, not everyone understands that it's only the unit price (£/kWh) that's been capped, not your actual annual bill. Prices are now reviewed quarterly.


The design proposal for the Spherical Tokamak for Energy Production (STEP) fusion reactor, the UK's first nuclear fusion reactor which will be built at West Burton, Notts.

A fusion future

As the energy market continues to evolve, Britain's new nuclear power fleet – now nearly half a century overdue – will incorporate Small Modular Reactors which will probably take ten years or so before they go onstream. Their modular approach allows production to be distributed around the country, and Rolls-Royce has already shortlisted seven potential sites for constructing three factories dedicated to manufacturing Rolls-Royce 470MW SMRs. The first, and largest factory will make the critical 'heavy vessels' themselves and two more factories will produce all the ancillary equipment needed. Thus, it will be possible to deliver SMR modules by road or rail, ready for final assembly on site (even, possibly, in anti-nuclear Scotland, which still has two nuclear power stations and has not yet ruled SMRs out).

The drive towards renewable and green energy continues, with the UK Government announcing an initial £20m investment into a pilot plant to explore whether nuclear fusion could become a commercial reality. A nuclear fusion power station would harness the energy of plasma generated at temperatures ten times greater than the sun and shaped by electromagnets within a *tokamak*, a Russian acronym that translates as 'toroidal chamber with magnetic coils'.

The fusion process is inherently safe in the sense that it cannot 'run away' and nuclear fusion has already been created in laboratory trials, but the process won't be commercially viable as long as it consumes more energy than it generates. The next stage of research is to build the UK's first prototype commercial nuclear fusion reactor. The site of an obsolete coal-fired power station at West Burton in Nottinghamshire, England

Nuclear fusion has been accomplished at laboratory level. The next step is to scale it up. (BBC/YouTube)

The multinational ITER nuclear fusion plant under construction in Provence. It is hoped that 'first plasma' will occur in 2025. (Photo: ITER Organization, April 2022)

has been chosen for a new Spherical Tokamak for Energy Production (STEP) fusion reactor, which the UK Atomic Energy Authority says will have many features of a fully operational power station. The research project is likely to be of comparable scale and value to a major operational power station, they add.

STEP will connect to the UK's National Grid and is expected to produce net energy (ie, more power than it consumes) although it is not expected to operate commercially at this stage. The first phase is to produce a concept design by 2024 as part of a 20-year research programme, and it should be commissioned by the late 2030s. A local BBC news clip explains more at **https://youtu.be/HOxunnbY75g** and the UKAEA describes the STEP proposals at **https://ccfe.ukaea.uk/research/step/**. An overview program (PDF) is downloadable at: **https://bit.ly/pe-dec22-ukaea**

Other research into nuclear fusion taking shape includes a huge multinational research project called ITER, which has been under construction in Provence, southern France since 2010 and will house the world's largest tokamak. It will be the CERN of the nuclear fusion world. It is hoped that 'first plasma' will take place in 2025 with full operation getting under way around ten years after that. There is a vast wealth of very interesting background information at the ITER website, see: **www.iter.org**

Back home, work continues in Britain to re-commission a major offshore gas storage facility, the 'Rough' field that was the largest gas storage asset in the UK, holding up to 70% of the nation's reserves. It closed in 2018 after Centrica, its operator and the owner of British Gas, discovered potential problems with some of the wells that fed into the gas storage field. The closure wasn't a simple case of short-sighted planning: the cost of remedial work was deemed too high and would have rendered the gas field commercially non-viable at that time. It is hoped that Rough will once again start to carry some reserves to meet at least some of the forthcoming winter demand.

Centrica has also announced plans to convert a decommissioned gas-fired power station hall at Brigg, North Lincolnshire, into a battery storage facility that could supply the equivalent of a full day's energy consumption for 11,000 households. America's GE is providing the 50MW/100MWh battery storage technology, which will store energy from the 43 onshore wind farms dotted around the county. The battery backup will help the UK's National Grid to store renewable energy and iron out peaks and troughs in the network, and it should be fully operational in late 2023.

(As an aside, the Brigg site was in fact a British Sugar factory from 1928 until the early 1990s, and as a young lad the author grew up in its shadow; they say smells are evocative and the pungent sweet smell of seasonal sugar processing drifted around while your scribe busied himself with a soldering iron in the garage. More than a dozen sugar factories eventually closed, a sign of progress.)

A smart socket

The brand TP-Link is well known for its wide range of entry-level and mid-range network peripherals. You'll find TP-Link switches and routers everywhere, together with a range of domestic smart bulbs, LED light strips, Wi-Fi security cameras and mains plugs and thermostats. So, still on the theme of saving energy, I've been trying out a 'smart' mains socket from TP-Link's budget Tapo range that has an energy monitoring function to help users keep an eye on power consumption.

tapo
MAX 13A
Wi-Fi
Wi-Fi Enabled (2.4 G Hz band)
Remote Control
Voice Control
Schedule and Timer
Away Mode
Share to Family
No Hub Required
Easy Use with Free APP

The TP-Link Tapo P110 is a budget smart socket with energy-monitoring features.

One feature of TP-Link's Tapo P110 'Mini Smart Wi-Fi Socket' is its compact size. The minimalist mains socket has a pushbutton but little else, and the UK version is rated at 13A, 2,990W (resistive), though European ones with a 16A Schuko socket are downrated to 10A, 2300W for some reason. It's a sealed unit, and although the label mentions a fuse, it's not user-serviceable so the socket would have to be thrown away if the internal fuse failed. They are probably not intended to control larger motorised appliances or anything containing a hefty power supply, but only time will tell how reliable they are.

I'm trying a couple of P110 smart sockets on my Mercusys/TP-Link home mesh network. The Tapo app needs installing on a smartphone or tablet using the same Wi-Fi network as the smart socket. The *Quick Start* guide consists of 'get the app' via a QR code, after which an online account must be set up. The Tapo app is generally easy to use and there was no problem finding the new smart socket on my network; you can also share the app with other family members on the same network. After automatically fetching a firmware upgrade, it was ready for use.

The app has a few handy features, some of which are hidden away a little. A 'Scheduler' acts like a weekly time switch function, although it can also be set to switch on or off at sunrise or sunset. An 'Away' mode is in fact a daily/weekly random timer cycle that can be set to make it appear that someone is home. A countdown timer can time the load for anything from a minute to 24 hours before switching it on or off.

The basic energy monitor logs power consumption in kWh for both today and the last 30 days. Tapping a data field (eg, 0.1kWh used today) opens bar graphs of usage from the past 30 days and 12 months. This function is hidden from view, and like one or two other aspects, is easy to overlook or forget about: there's a log of the on-off history buried in the Shortcuts menu.

Alexa, turn on the lights

The smart socket is both Alexa and Google Assistant compatible, so it can be operated via voice control with a smart speaker. Various 'smart actions' and automation routines are built in, and it appears that Tapo is now IFTTT (If This, Then That) compatible. See **https://ifttt.com/tplink_tapo** for a small number of IFTTT automation routines. The TP110 smart plug costs typically £10 if you shop around, and more details are at: **https://bit.ly/pe-dec22-tapo**

A cheaper Tapo smart socket (the TP100) does not include energy monitoring. The Tapo line-up includes Wi-Fi cameras and a trial of unlimited cloud storage (Tapo Care) starts at £2.99 a month for six months or £25.99 a year for one device (£93.99 per annum for up to five devices). TP-Link also lists an older range of 'Kasa' smart devices which needs the Kasa app instead. The Kasa equivalent of the TP110 is the KP115 Mini Smart Plug with energy monitoring.

Unfortunately, a lot of misleading or outdated information about these ranges will be found online, but the Kasa and Tapo platforms are incompatible so it's easiest to stick with one line or the other. The Tapo line is the cheaper, entry-level system of the two which will be adequate for many users wishing to add a smart device or two, to control small appliances, tabletop lights or radios, especially using Alexa or Google to control them. Kasa seems a bit more robust and has many more IFTTT routines available, which might appeal to more advanced users. I also noticed that the Kasa Smart Wi-Fi Plug (HS100) that I have on the bench does have a replaceable fuse. A device similar to TP-Link's range would be the Tenda SP9 smart socket, which has energy monitoring features.

Apart from smart sockets, there are countless energy-monitoring plug-in adaptors with built-in LCDs that display and log power consumption. The versatile Brennenstuhl PM 231 Wattage & Current Meter displays voltage, frequency, current, power factor (cos ø) and power output, and it calculates the total energy consumption, running costs (with day and night tariffs) and runtime. My older version (PM 230) informs me that my smart TV draws 9W on standby (ongoing, that'll be £25 a year) and over 140 days my telly swallowed 87kWh or £16 worth at 2021 prices, or double that, looking ahead.

Due to the design, it may not fit some British mains wall sockets that are near floor level. The mono LCD is not backlit, and my PM 230 had no fuse protection inside. It's informative though, and a battery backup maintains settings and data. The UK manual of the PM 231 can be downloaded from **https://bit.ly/pe-dec22-pm231**. There are many unbranded alternatives on Amazon and eBay.

The Queen's email

Following my feature last month celebrating some technology milestones in the reign of the late Queen Elizabeth II, my thanks go once again to regular *PE* reader Godfrey Manning who shares some memories:

'I noticed the late Professor Peter Kirstein was credited with the photo on page 12 of HM Queen Elizabeth II sending an email at RSRE. As an undergraduate at UCL (intercalated BSc Medical Statistics & Computer Science, 1977/78) I worked in the same department as Prof. Kirstein. I'd heard of ARPANET (possibly JANET – the Joint Academic Network – too) but such an advanced research project seemed out of my grasp and I felt that it (and the Professor) were rather distant – or, at least, beyond what someone like me could be involved in!

'Our only network connection to remote computers was by RS-232, often 300 baud over an acoustic coupler telephone modem. We were grateful for what we had! As to Her Majesty's VDU, could it be one of those made by Newbury? Yes, Britain could still produce such things in those days. Also in my career, from 1982-84 I worked on a hospital path-lab system written in the (wholly unsuitable!) CORAL-66 as also seen in your photo. Regards ('73' as we radio amateurs say in Morse), Godfrey Manning G4GLM, Edgware.'

8.8.8.8.8
188
88:88
RESET
UP
SET
FUNC
brennenstuhl

Brennenstuhl's PM 231 meter measures power usage, efficiency and costs, along with other useful parameters (UK version shown).

Thank you for writing, Godfrey – can anyone identify the terminal monitor the Queen used when sending her first email?

Once again, my column inches have been filled, so that's all for this month's *Net Work*. Do remember that this article's web links will be ready-made for you to click on in the *Net Work* blog available at: **www.electronpublishing.com** – see you next month!

The author can be reached at:
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The Hum
Audio A

Like a hummingbird, this miniature amplifier is nimble, small in size but strong, delivering up to 60W into 8Ω or 100W into 4Ω. It is ideal for

Readers frequently ask us for advice on building amplifiers with more than two channels. We've published many Hi-Fi amplifier module designs over the years, but mainly they have been designed for maximum power and minimum distortion, resulting in modules that will only fit one or two per case (unless you use a huge case!).

We have published amplifier designs using all-in-one IC 'chip' amps like the LM1875T. They are always quite compromised, both in terms of maximum power output (typically topping out at around 30-40W) and performance, with distortion and noise figures far worse than a discrete amplifier.

This design offers an excellent compromise between the two. It's cheaper and easier to build than our best Hi-Fi amplifiers while still delivering plenty of power with very good performance. And because it's so compact and has modest power supply requirements, you can quite easily jam half a dozen (or more!) of them into a reasonably sized chassis.

We designed these for driving multi-way loudspeaker systems using an active crossover to split the signals into frequency ranges to suit each driver. This approach needs one amplifier per driver (woofer, tweeter and so on) but you generally don't need as much power per amplifier, since they are working together.

Initially, we looked at using small, low-cost Class-D amplifier modules which could deliver 30-50W. After quite a bit of searching, we concluded that there was nothing readily available with distortion performance within an order of magnitude of what we'd call 'Hi-Fi'. Many smaller Class-D amplifiers exhibit high-frequency distortion above 0.5%, worse than many decent loudspeaker drivers!

In the end, we looked at larger high-quality amplifiers and shrunk the design. The result is the *Hummingbird Amplifier Module*, which packs a surprising punch for its size, while keeping many of the low-distortion characteristics of the larger amplifiers from which it takes inspiration. It can achieve up to 60W into 8Ω or 100W into 4Ω with distortion below 0.0008% at 1kHz and less than 0.008% all the way up to 20kHz. That's way better than 'CD quality'.

Design

If you are familiar with larger amplifier topology, then an examination of the circuit diagram (Fig.7) will show many similarities between the *Hummingbird* and larger siblings. On the other hand, for compactness, the principal differences are:

- We opted for one pair of output transistors, rather than two

Features

- Low distortion and noise
- Extremely compact PCB
- Fits vertically on a 75mm heatsink and can be stacked in a 2RU case
- Produces specified power output continuously with passive cooling
- All through-hole parts
- Low in cost, simple to build
- Onboard DC fuses
- Output over-current and short-circuit protection
- Clean overload recovery with low ringing
- Clean square wave response with minimal ringing
- Tolerant of hum and EMI fields
- Quiescent current adjustment with temperature compensation

Specifications

- Output power (±32V rails): 100W RMS into 4Ω, 60W RMS into 8Ω
- Frequency response (–3dB): 1Hz to 150kHz
- Signal-to-noise ratio: 118dB with respect to 50W into 4Ω
- Input sensitivity: 1.2V RMS for 60W into 8Ω; 1.04V RMS for 100W into 4Ω
- Input impedance: 22kΩ || 1nF
- Total Harmonic Distortion (8Ω, ±32V): <0.008%, 20Hz-20kHz, 50kHz bandwidth 32W (see Fig.2 and Fig.6)
- Stability: unconditionally stable with any nominal speaker load ≥4Ω
- Power supply: ±20-40V DC, ideally ±34V DC from a 25-0-25 transformer
- Quiescent current: 53mA nominal
- Quiescent power: 4W nominal
- Output offset: typically <20mV (measured)

mingbird
mplifier

building multi-channel amplifiers for applications like surround sound or when using an active crossover. Despite its compact size, only a few compromises were made compared to much larger designs – it even has output protection!

Image Source: https://pixabay.com/photos/hummingbird-bird-flight-wings-2139279/

By Phil Prosser

- We chose inexpensive NJW21193/4 output transistors
- The maximum supply rail voltages are just ±40V (larger amplifiers often go to ±60V).

It's also worth noting that the PCB is not large – just 64mm wide – and circuit simplification lets us use through-hole components exclusively.

The width of the PCB is defined by the two output devices and thermal compensation transistor. This is also a neat fit for the emitter resistors required for a stable operating bias point.

Despite their relatively large size, we have used DC rail fuses in this design, as they form an important protective layer for the amplifier in case something goes wrong in use.

The SOA protection is tightly coupled with the output stage and sits between this and the voltage amplifier stage (VAS). The VAS and driver come next, and sit between the fuses, again with little room to spare. At the front end of the board is the input stage. How the various sections of the amplifier fit on the PCB is shown in Fig.1.

We are only using one output device per side, so we have chosen a robust device with a generous safe operating area (SOA). Few devices are sturdier than the NJW21193G/NJW21194G (or their beefier MJL21193/4 siblings). These are rated at 16A, 250V and 200W.

We decided to add output SOA protection to the amplifier that monitors the output current and voltage and shuts off the output in case of a short circuit or severe overload. This protects the amplifier from all but the worst abuse.

Calculations confirmed that using a mains transformer with a 25-30V AC secondary providing rail voltages of ±35-42V would be safe with a single pair of output devices into 4Ω, 6Ω or 8Ω, delivering 60W into 8Ω loads and 100W into 4Ω loads. With a 25V transformer, that's reduced slightly to 50W for 8Ω.

For those of you who follow audio amplifier design, the topology here is basically the 'blameless' amplifier (as it is dubbed by Douglas Self), which just works. The innovation in this project is more about our aproach to simplification and minimisation.

No doubt using SMDs would have let us make the PCB less, err, packed.

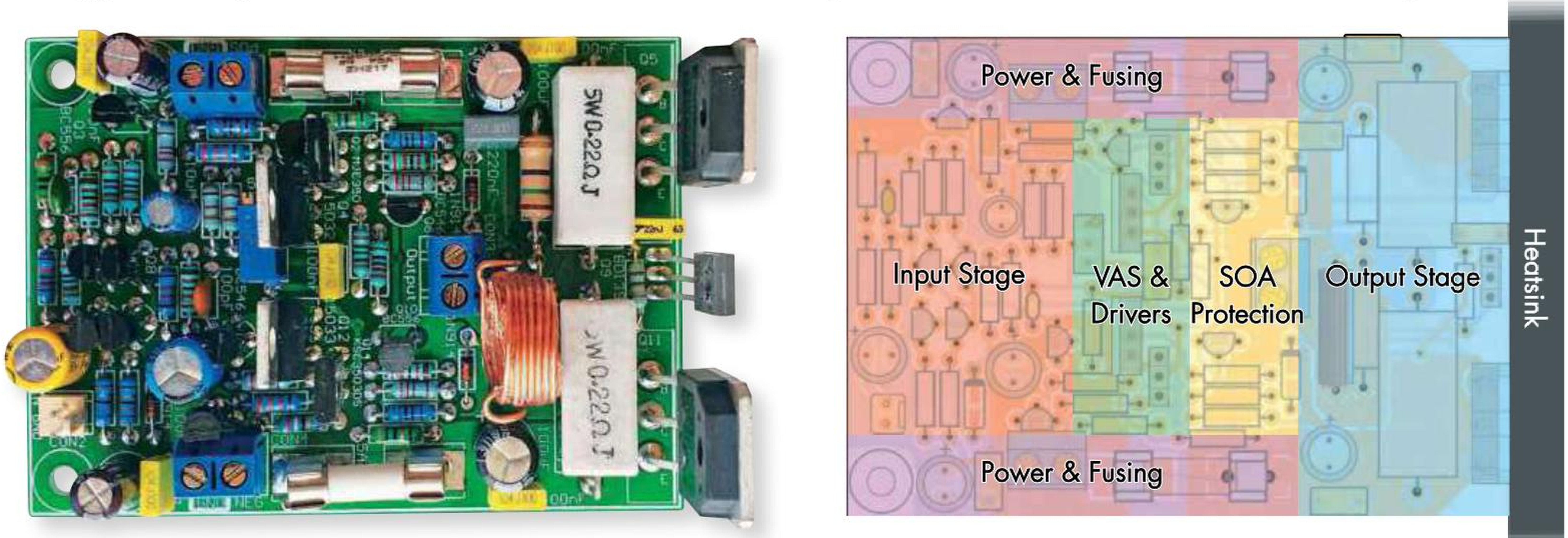


Fig.1: this depiction of the Hummingbird PCB is at 90% of life-size and shows the purpose of each set of components. The input stage is responsible for setting the gain and distortion cancellation while the VAS and drivers buffer the signal from the input stage to provide suitable drive for the output transistors. The SOA protection circuitry keeps the output transistors within their 'safe operating areas'.

Still, we managed to fit all the required through-hole components into an area of just 88 by 64mm. That will easily fit standing on its side in a standard two rack unit (2RU) high case, and assembly is not especially difficult.

Performance

We took total harmonic distortion (THD) measurements of the prototypes at 10W and 35W into 8Ω by powering it from a bench supply, shown in Fig.2. The 35W measurement required using a 40dB attenuator with our test equipment, while the 10W level only needed a 20dB attenuator. That is why the distortion results at 10W look so much better than at 35W.

Given that the shapes of the two curves are very similar, it's likely that the actual performance of the amplifier is closer to the 10W figures, even up to its maximum 60W power output. We can confidently say that this amplifier generates very low distortion levels, and at 10W, is below 0.002% THD over much of the audio range.

Note that Fig.2 also shows partial distortion curves for various alternative output/driver/VAS transistors, and we will explain those options a bit later.

The amplifier behaves well at clipping. The most common problem is the output 'sticking' as the amplifier exits clipping from the negative rail, when the VAS transistor comes out of saturation. The *Hummingbird* behaves well coming out of clipping, as shown in Fig.3 and Fig.4.

We also tested with a square wave signal, and the result is in Fig.5. There is not a lot to show here; it generates a bandwidth-limited square wave output as shown, with no overshoot and minimal undershoot.

Finally, Fig.6 shows one of the spectral plots taken while gathering the measurements for Fig.2. The left channel is connected to the output of the amplifier via an attenuator, while the right channel is monitoring the signal into the amplifier. As you can see, the distortion at the output is hardly any higher than the input signal, and the second and third harmonics are roughly equal at around –110dB.

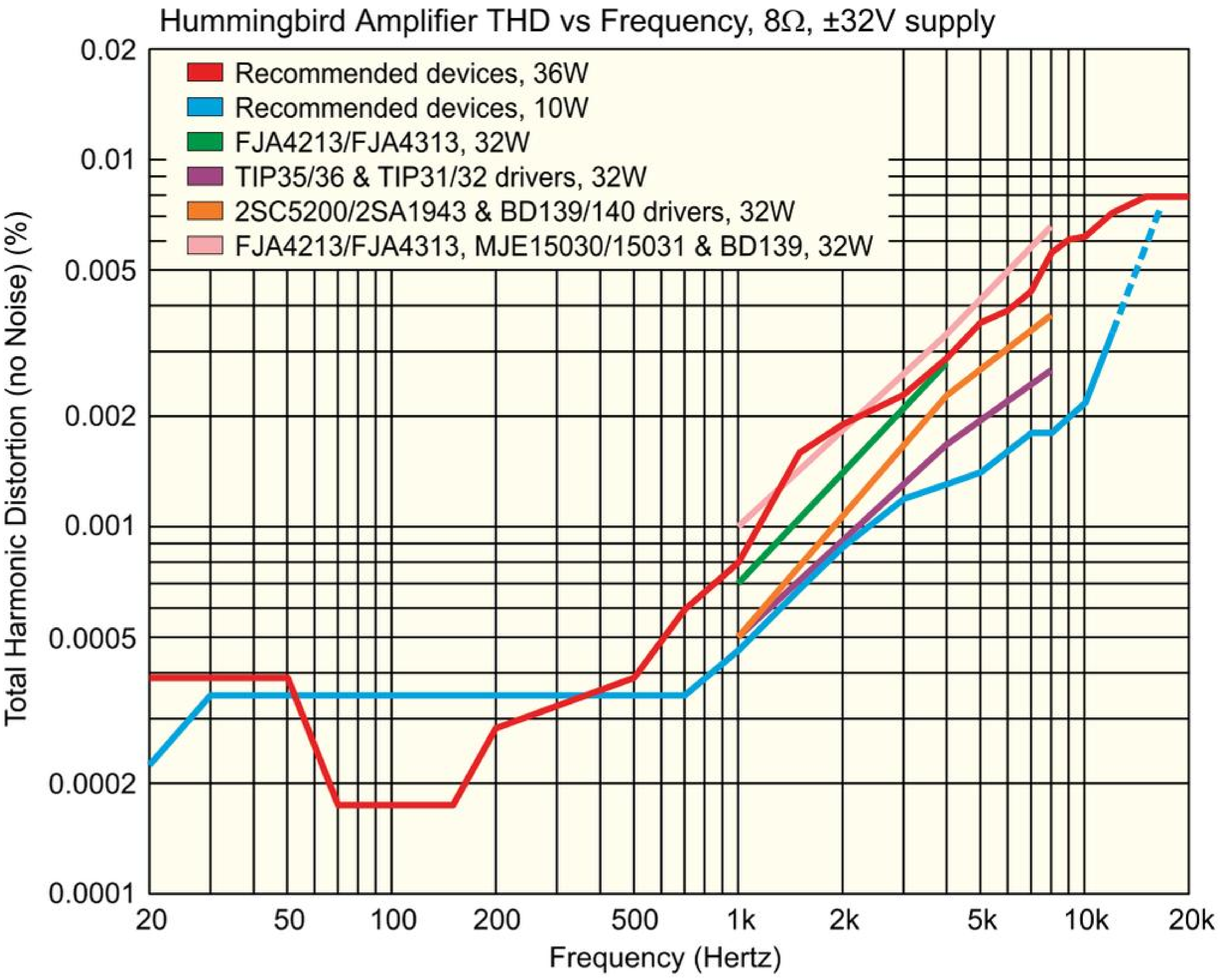


Fig.2: total harmonic distortion (minus noise) plots for the Hummingbird at two different power levels: 36W (red) and 10W (blue). The other curves show the test results with various combinations of output transistors, driver transistors and, in one case, a different VAS transistor (BD139, pink curve). Regardless of which devices you choose, the performance is pretty good.

Circuit description

Fig.7 shows the *Hummingbird* circuit. A 220kΩ resistor biases the input signal at CON2 to 0V DC. The input signal passes through a 10µF bipolar capacitor and then a 100Ω resistor shunted by 1nF and 22kΩ to the low-noise signal ground. This connects to the output ground via a 10Ω resistor. The 10µF and 22kΩ combination at the input sets the –3dB low-frequency cutoff point below 1Hz.

The 22kΩ input resistor is selected to match the 22kΩ feedback resistor so that each side of the differential amplifier formed by PNP transistors Q7 and Q8 has matched DC input impedances. Assuming that these transistors have equal current through each leg and similar h_{FE}, the offset voltages at the bases of Q7 and Q8 will be about the same.

This should ensure a low output offset voltage on the amplifier. We measured less than 20mV on our prototypes.

We have specified BC556 transistors for Q7 and Q8, although you could use low-noise BC560 devices if you can find them. These are commonly available and perform well in this application. 100Ω emitter degeneration resistors are used for Q7 and Q8. These

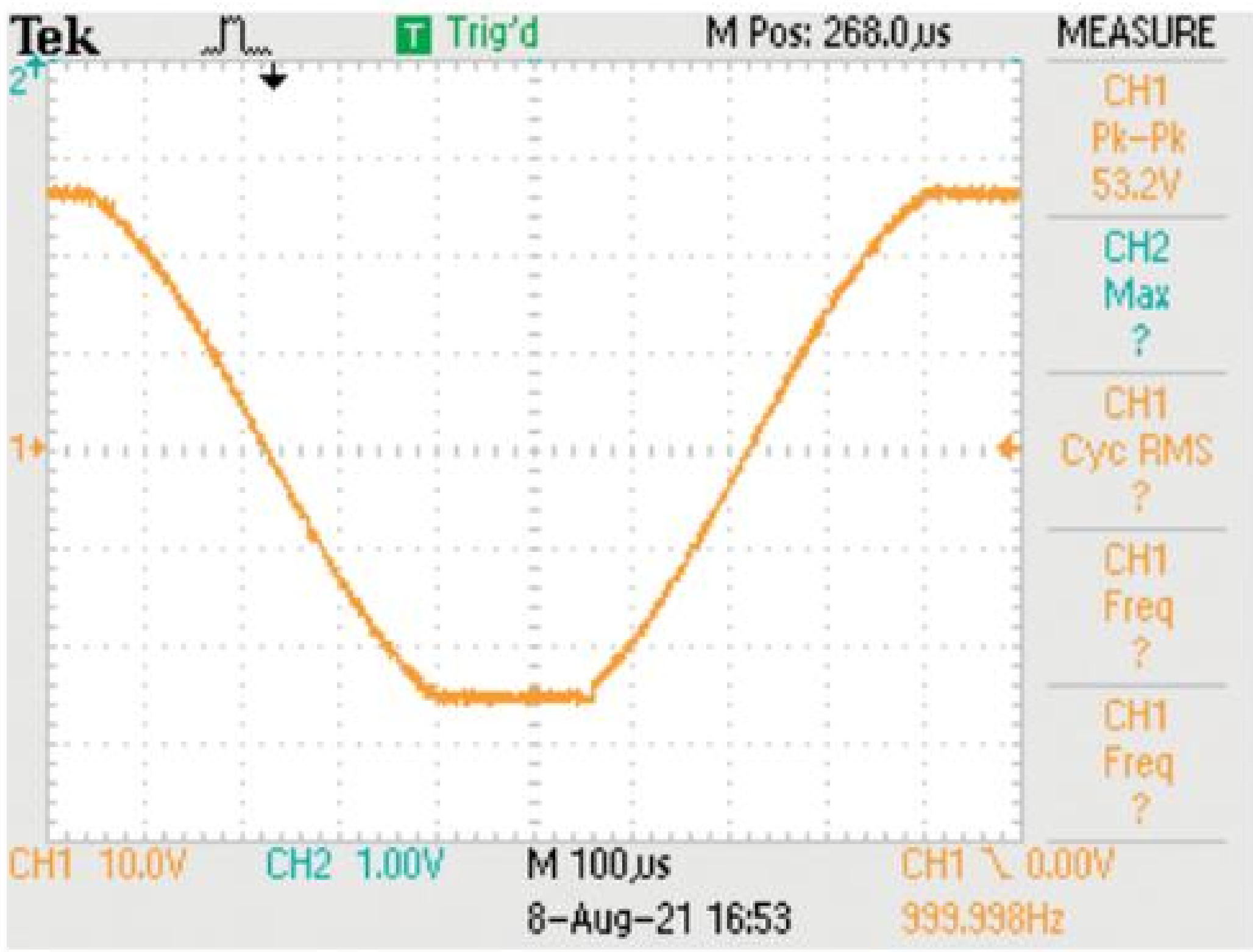


Fig.3: a scope plot of the amplifier's output waveform into an 8Ω resistive load, driven into clipping. You can see there's a tiny bit of 'sticking' to the negative rail as it comes out of clipping, but not enough to be concerned about.

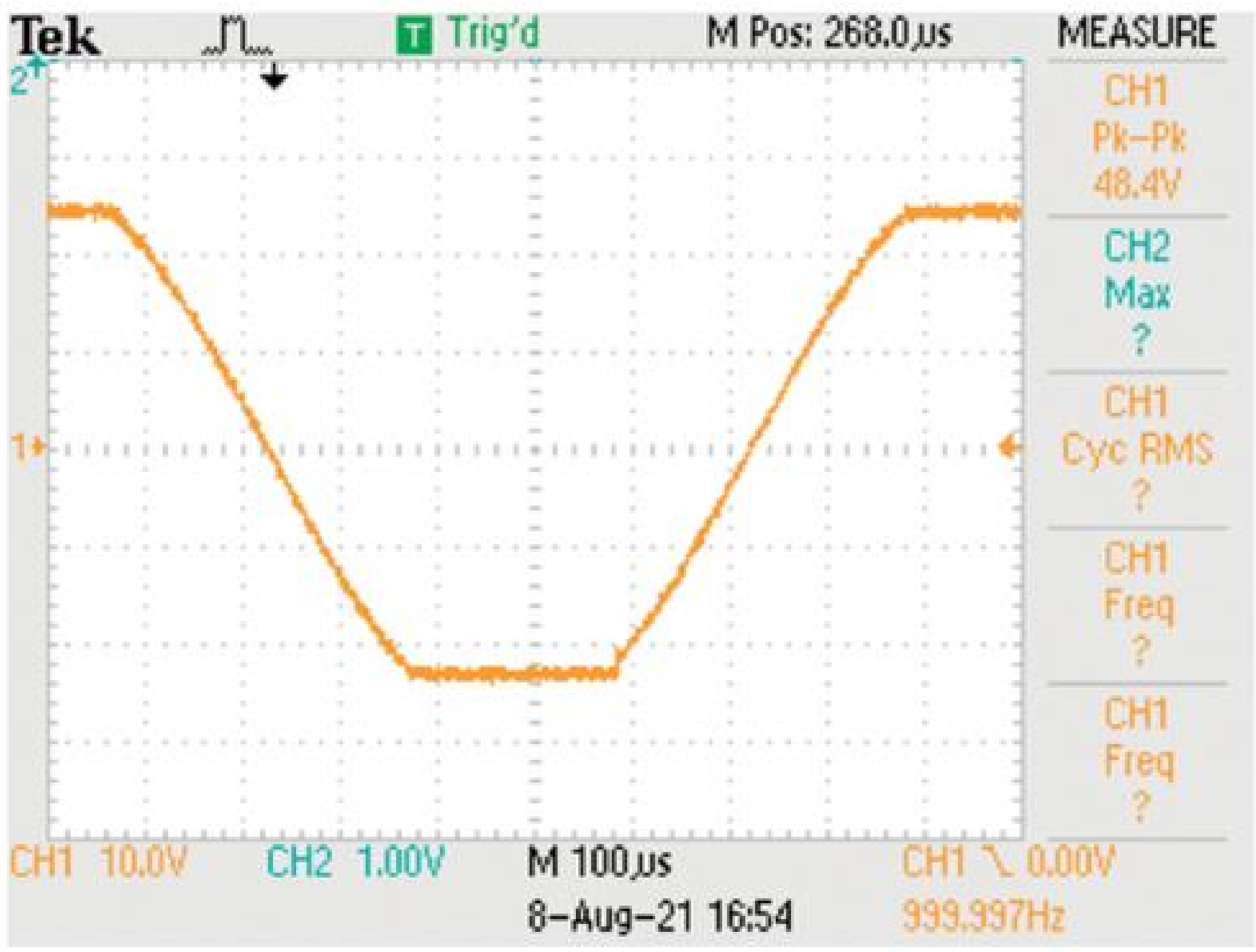


Fig.4: this time, the amplifier has been driven into clipping with a 3Ω resistive load, representing pretty much the worst-case situation it will have to deal with when driving a real 4Ω (nominal) loudspeaker. Once again, the recovery from clipping is fine.

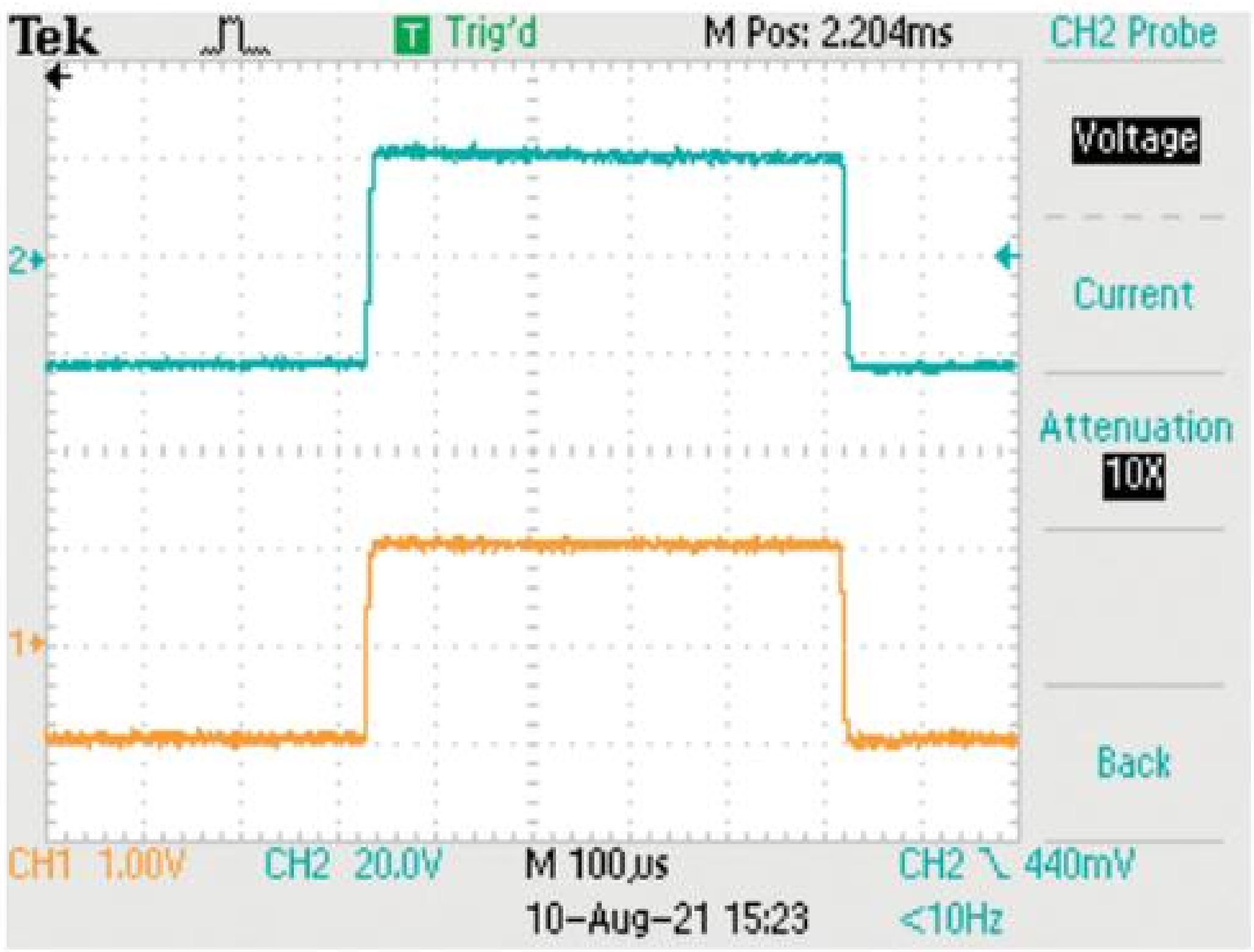
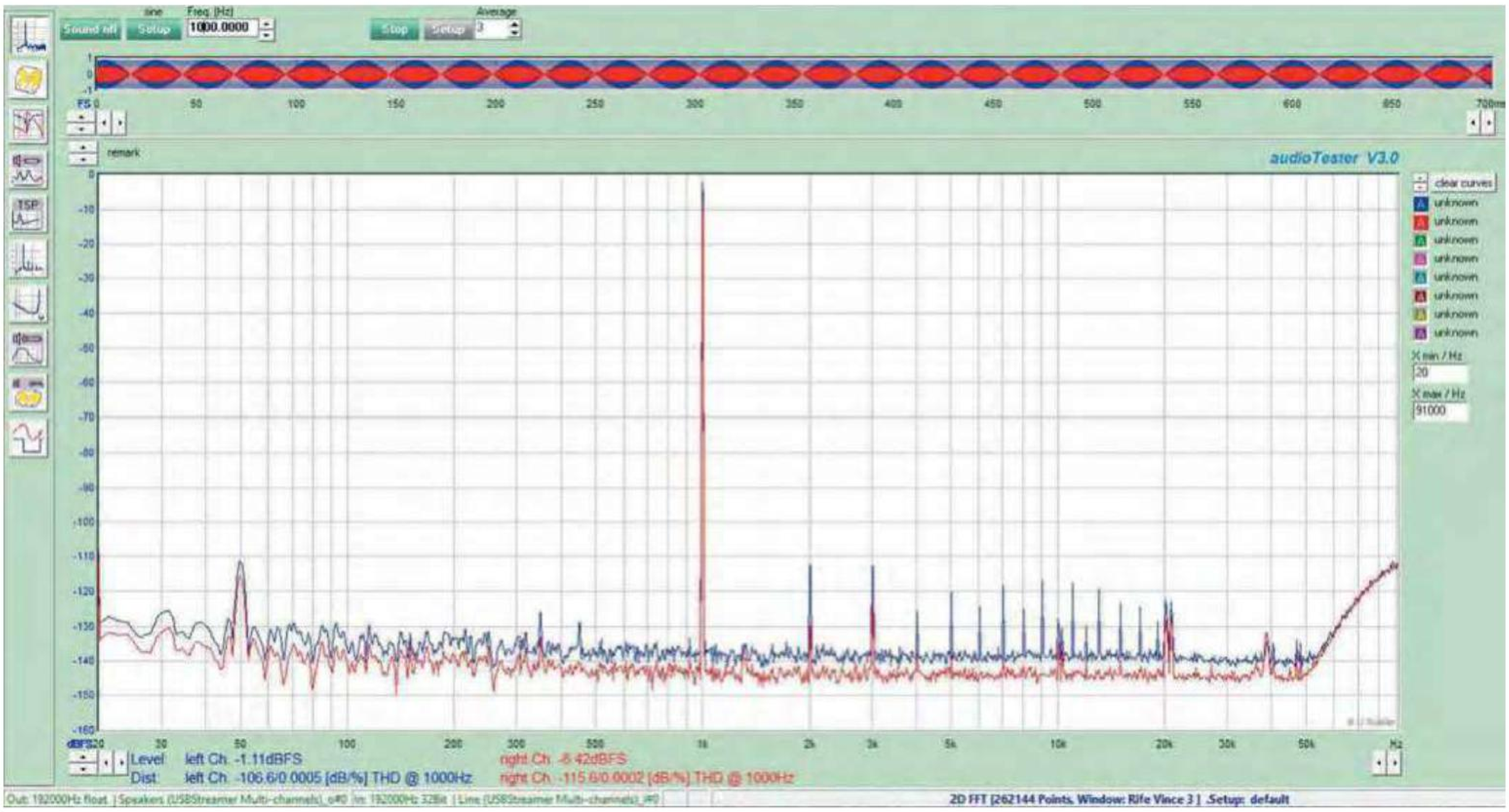


Fig.5: we fed a square wave signal (orange) into the Hummingbird and connected its output to a 3Ω resistive load (harsh, we know). It handled this very well, with no sign of overshoot or undershoot; clearly, it's a very well-behaved amplifier.



```
Level   left Ch. -1.11dBFS                                  right Ch. -8.42dBFS
Dist    left Ch. -106.6/0.0005 [dB/%] THD @ 1000Hz          right Ch. -115.6/0.0002 [dB/%] THD @ 1000Hz
2D FFT [262144 Points, Window: Rife Vince 3 ] .Setup: default
```

Fig.6: one of the many spectral plots we produced as part of the performance tests. You can see the THD readings of the input (red) and output (blue) signals towards the bottom. You can also see all the harmonics of both signals in the central area. The test signal is at 1kHz, so the first harmonic is at 2kHz, third at 3kHz and so on. The amp's output was passed through a 40dB attenuator, reducing the fundamental to –15dB and dropping the measured noise floor to that of the instrument.

assist with achieving balance and linearity in the differential amplifier. This reduces its sensitivity to transistor and temperature variations.

The input stage operates with 3mA of bias current. This is set by the 220Ω resistor in the emitter leg of PNP transistor Q3, which serves as a constant-current source.

The keen-eyed will note that we have omitted a resistor from between the constant-current source and the differential amplifier. Our lower voltage rails mean this is not necessary, as Q3 can handle the resulting 100mW dissipation.

The collector legs of the differential amplifier feed into a current mirror made using NPN transistors Q15 and Q16. A current mirror works by exploiting the fact that with a matched set of transistors at the same temperature, the V_{BE} (base-emitter voltage) relationship vs current will be the same.

So by connecting the bases of Q15 and Q16, and putting the same resistance in their emitter circuits, if we drive 1.5mA through Q16, Q15 will similarly seek to conduct 1.5mA as it has the same base-emitter voltage.

This ensures that the differential pair of Q7 and Q8 operates with the same current in each leg, which means it operates optimally as a linear differential amplifier.

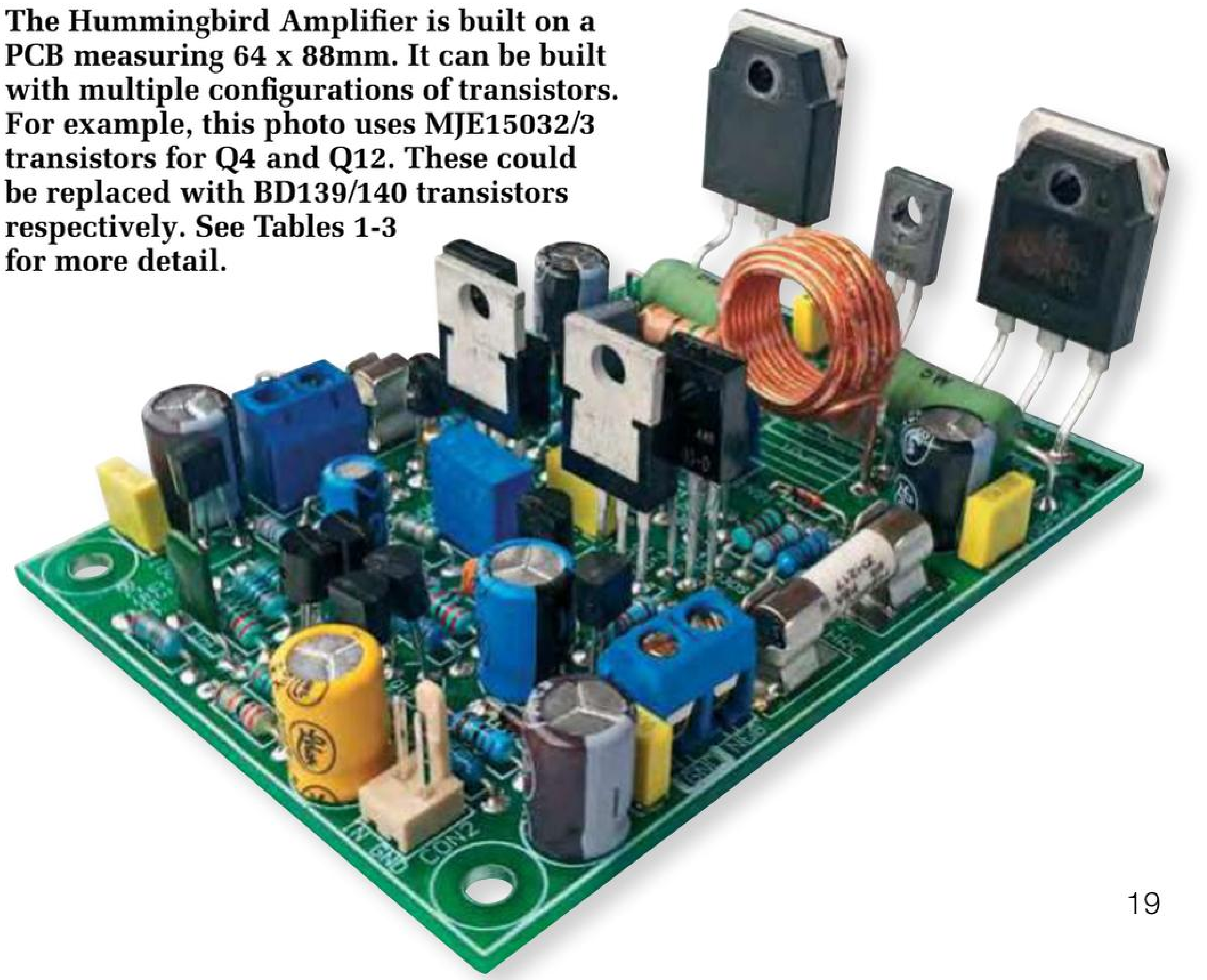
The output of the differential amplifier is a current that flows into the base of NPN transistor Q13. If the amplifier output is higher than the input, the input to Q8 increases, which reduces the current into Q16. Because the current mirror 'tries' to keep the current through Q15 and Q16 the same, this excess current flows into Q13's base.

Q13 forms part of a quasi Darlington transistor pair with Q14, which ultimately drives the amplifier output. These transistors together form the voltage amplifier stage (VAS). It transforms the current from the front end into a voltage.

Q14 is a KSC3503DS transistor, which is specialised for this sort of application. These are available from Mouser, Digi-Key, element14 and RS. The VAS transistor needs to have a very low C_{OB} or output capacitance.

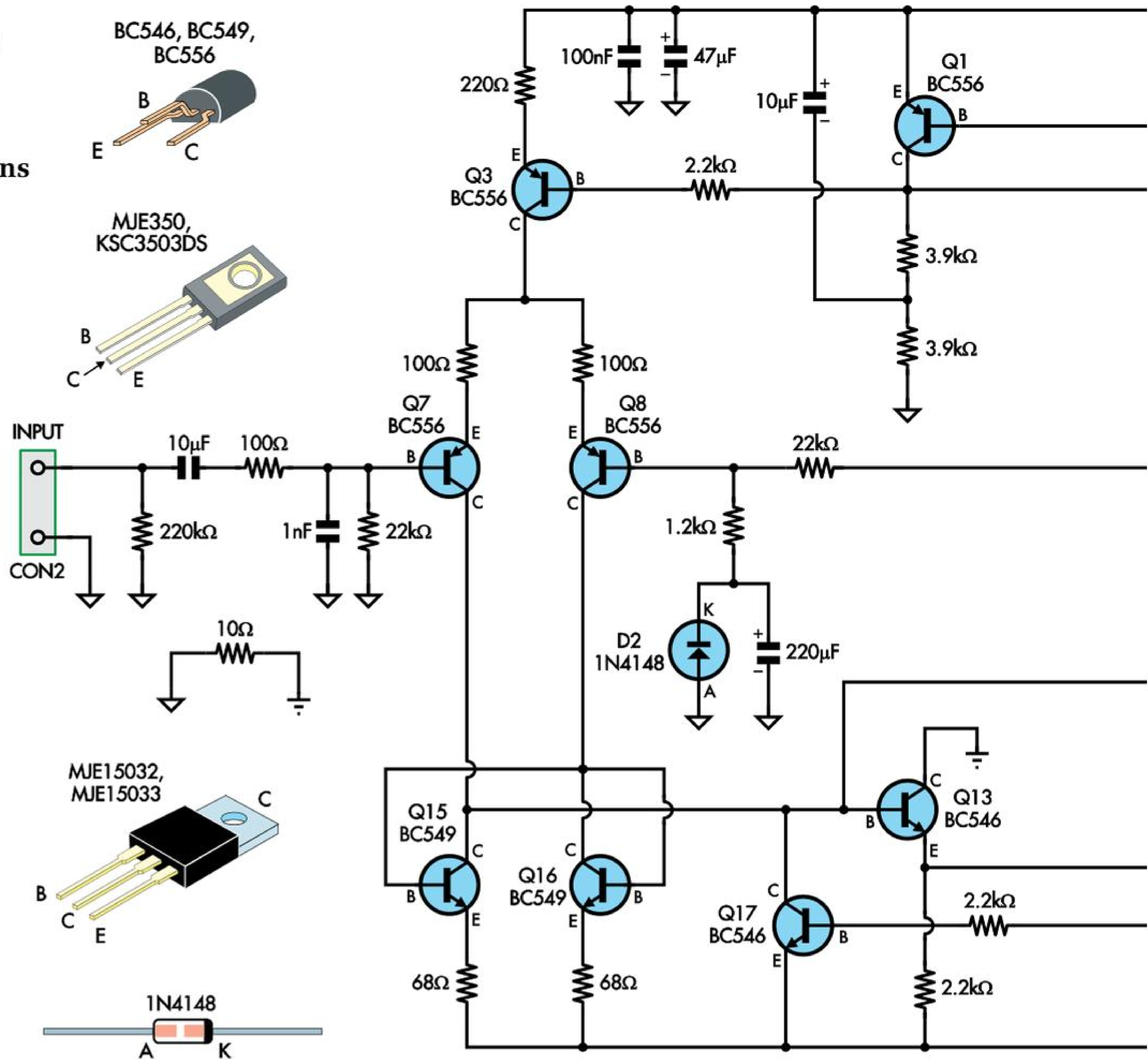
There are not many really suitable devices being made these days, most likely as the best VAS transistors were also video amplifier transistors for cathode ray tube (CRT) monitors, which have gone the way of the dodo! We used the BF469 video transistor here in the past, but they are now obsolete.

The load on the VAS is the constant current from PNP transistors Q1 and Q2, which is set to about 8mA, plus the current required to drive the output stage.



The Hummingbird Amplifier is built on a PCB measuring 64 x 88mm. It can be built with multiple configurations of transistors. For example, this photo uses MJE15032/3 transistors for Q4 and Q12. These could be replaced with BD139/140 transistors respectively. See Tables 1-3 for more detail.

Fig.7: the Hummingbird amplifier circuit is pretty standard if a bit minimalist. It has a lot in common with our previously published, higher-power amplifiers like the SC200. Note NPN transistor Q17, which has been added to protect Q14 during negative clipping excursions and the SOA protection transistors, Q6 and Q10, with three resistors each to set the I/V limit slope and intercept.



Hummingbird 100W Amplifier

Between Q2 and Q14, we have NPN transistor Q9 and its base-biasing resistors. This forms a simple 'V_{BE} multiplier' that allows us to set the voltage between the bases of the output stage and driver transistors Q4, Q5, Q11 and Q12. These are arranged in standard emitter-follower connected pairs.

The amplifier must operate in Class-AB for good performance, where both the positive (NPN) and negative (PNP) output devices are conducting for output voltages around the 0V crossover point, as shown in Fig.8. We want to bias the amplifier to draw about 50mA in the quiescent state as this gives the best output stage linearity around the crossover point.

To achieve this, we need to set a 'constant' voltage to bias the four base-emitter junctions at just over their turn-on voltage (about 0.6V each), for a total of around 2.4V.

But the base-emitter threshold voltages of Q4, Q5, Q11 and Q12 all vary with temperature, so Q9 is mounted on the same heatsink as Q5 and Q11, and Q9 is used to multiply its own V_{BE} voltage using a 390Ω fixed resistor and potentiometer VR1. This way, the bias voltage will track the V_{BE} voltages of those two transistors, giving a mostly constant bias current.

When properly adjusted, VR1 will be about 130Ω. Q9's base-emitter voltage is across this resistance, around 0.6V, giving about 4.6mA through VR1 and also the 390Ω resistor. That gives 1.8V (390Ω × 4.6mA) between Q9's base and collector, for a total of 2.4V (0.6V + 1.8V).

Our output stage is a single pair of transistors, Q5 and Q11. The NJW21193/4 types, as stated earlier, have been selected for their SOA large (safe operating area). These are driven by MJE15032/33 driver devices, as there is not enough current available from the VAS to drive them directly.

The output devices both have 0.22Ω resistors in series with their emitters,

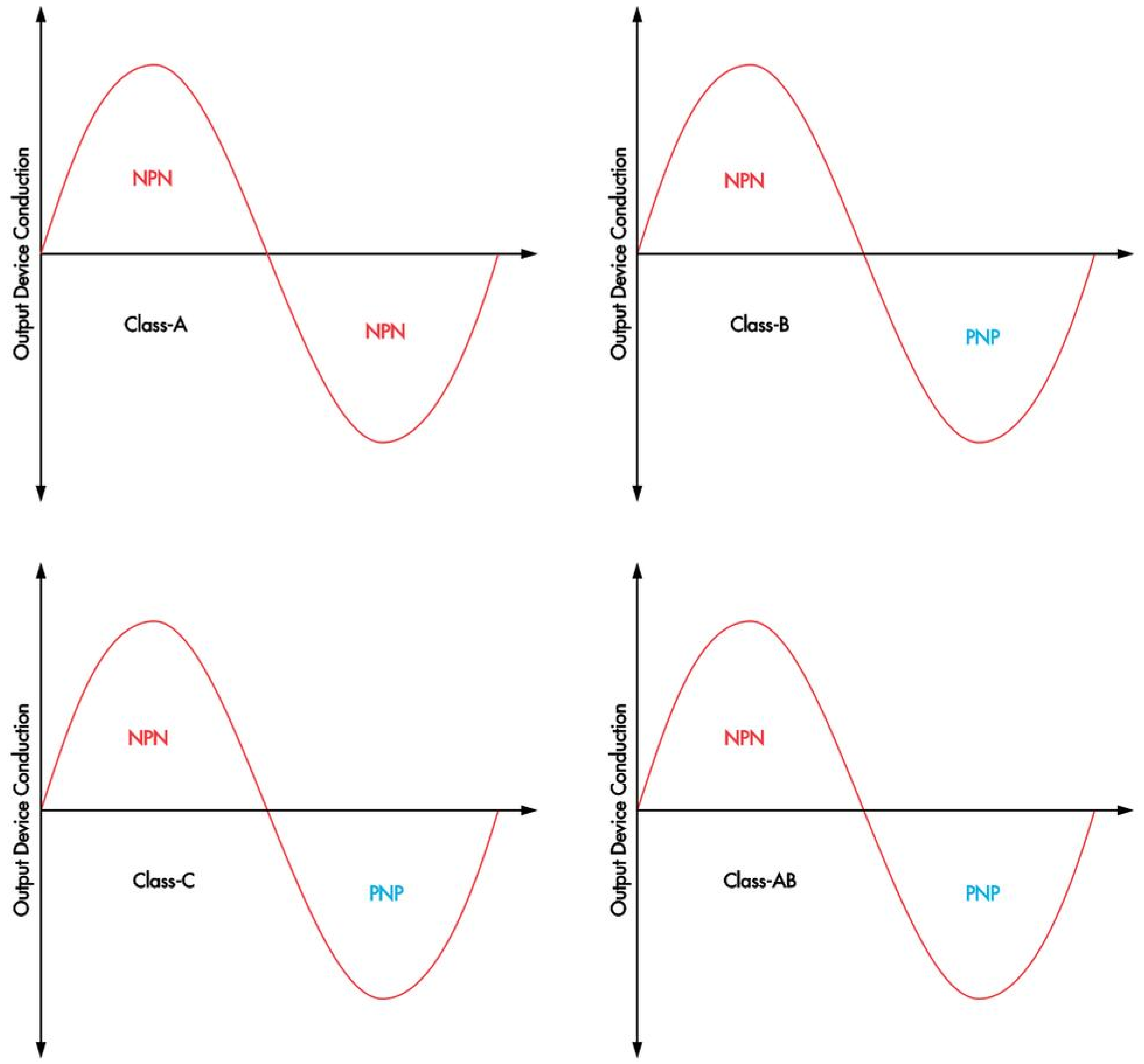
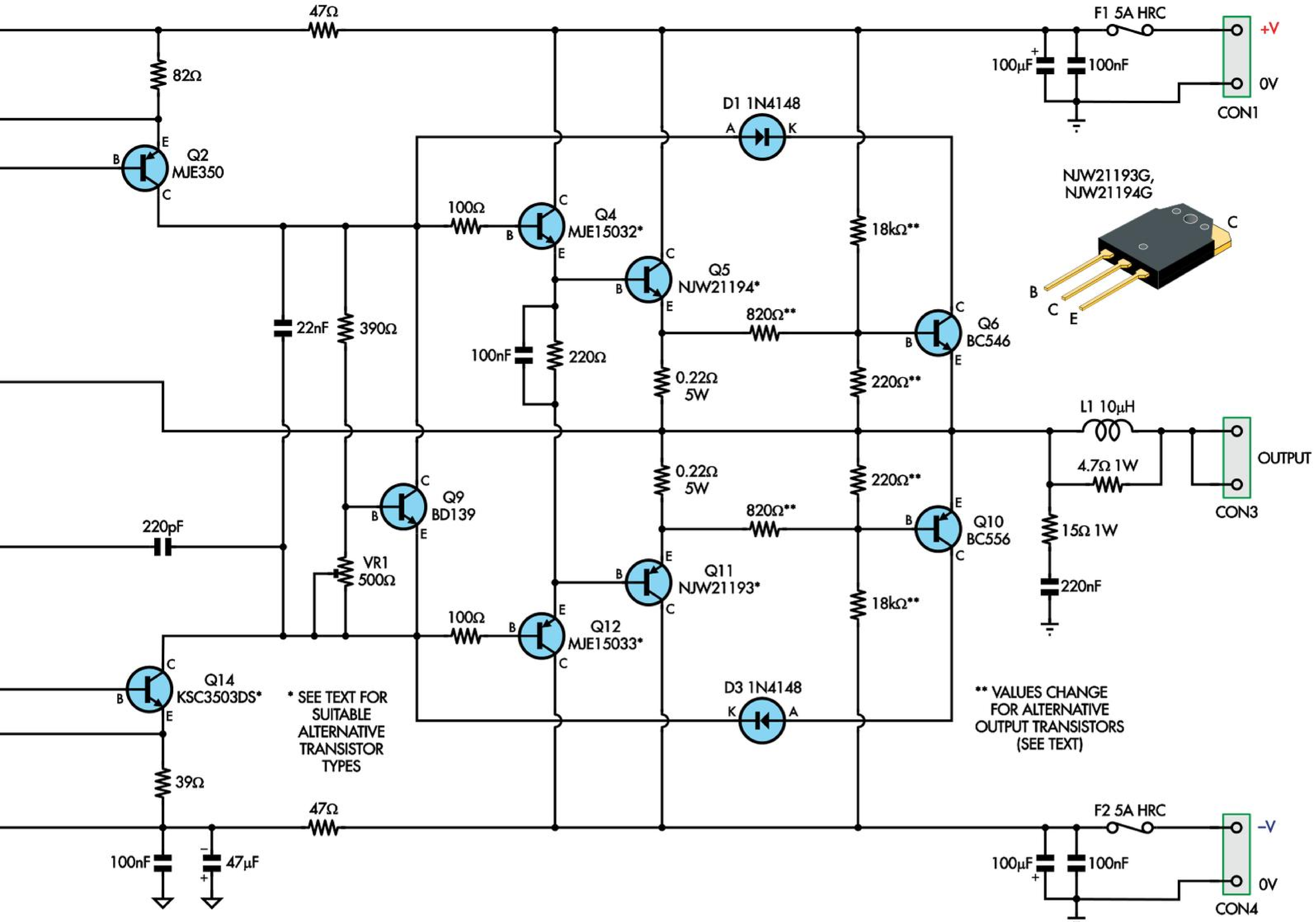


Fig.8: four common amplifier classes; Class-C is mainly used for RF, not audio, where distortion is less of a concern. Class-A has a single transistor that varies its conduction over the whole cycle, while the other three classes use complementary pairs. In Class-B, one device conducts for the positive half of the cycle; the other conducts during the negative half. Class-AB is like Class-B except that both devices conduct when the output is near 0V (the purple area is where they overlap), while for Class-C, neither device conducts in the crossover zone.


47Ω
82Ω
F1 5A HRC
+V
100µF
100nF
0V
CON1
D1 1N4148
A
K
Q2
MJE350
B
E
C
NJW21193G,
NJW21194G
B
C
E
C
100Ω
Q4
MJE15032*
Q5
NJW21194*
18kΩ**
820Ω**
Q6
BC546
22nF
390Ω
100nF
220Ω
0.22Ω
5W
220Ω**
L1 10µH
4.7Ω 1W
OUTPUT
CON3
0.22Ω
5W
220Ω**
Q9
BD139
220pF
820Ω**
Q10
BC556
15Ω 1W
VR1
500Ω
Q11
NJW21193*
220nF
100Ω
Q12
MJE15033*
18kΩ**
Q14
KSC3503DS*
* SEE TEXT FOR SUITABLE ALTERNATIVE TRANSISTOR TYPES
D3 1N4148
K
A
** VALUES CHANGE FOR ALTERNATIVE OUTPUT TRANSISTORS (SEE TEXT)
39Ω
47Ω
F2 5A HRC
–V
100nF
47µF
100µF
100nF
0V
CON4

providing a small amount of negative feedback for their bias currents.

The driver devices are capable of much higher current and dissipation than demanded in this application. However, they are widely available and reasonably priced, so they suit this application well. They do not dissipate enough power in this application to require heatsinking.

However, suppose you are pushing your luck by increasing the rail voltage or driving very low impedances with continuous waveforms, or you wish to achieve ideal bias tracking. In that case, you might benefit from fitting them to the heatsink (or the back of the output devices) on flying leads.

Ideally, we would have mounted them on the main heatsink so that their V_{BE} voltages track those of the output devices, as Q9 will multiply its own V_{BE} changes by a factor of four. We did not do that, to keep this module as compact as possible.

The driver transistors still heat up and cool down as the load changes, which provides some thermal tracking, but it won't be exact.

The result is that under transient application of a heavy load, the output stage bias will tend to decrease slightly as the module gets hot delivering a significant amount of power. It does not experience thermal runaway, nor does the performance change due to this change in bias, so it is a worthwhile compromise to keep the module compact.

SOA protection

We are using a single pair of output devices so we feel it prudent to protect them against unexpected overload or short circuits. Shorting the output of a typical amplifier often leads to the failure of output devices, driver transistors and ultimately the fuse, often in that order. We get around that by adding some basic safe operating area (SOA) limiting components.

The SOA curves for each pair of recommended output devices (taken from their data sheets) are plotted in Fig.9 and Fig.10, along with curves representing the maximum specified output power being delivered into purely resistive and reactive loads, the latter represents worst-case loudspeaker load.

As you can see, except for the TIP35/36 pair, all devices will be within their SOAs under these conditions. However, some loudspeakers can have significant impedance dips at specific frequencies that could cause the transistors to operate outside their safe areas, and also accidents can happen with the wiring (accidental shorting together).

Fig.11 shows the same SOA curves as Fig.9 and Fig.10, but also adds dashed 'SOA protection' lines. These are the limits we've chosen to 'program in' for each pair of output devices to ensure they stay within their SOAs.

The effect of driving the *Hummingbird* into a 1Ω load is shown in Fig.12. The input signal is at the top, while the 'clipped' output waveform below shows the protection kicking in. This will not save you from ultimately overheating the output transistors, but it will prevent the immediate loss of 'magic smoke'.

Some people claim that this type of protection degrades the amplifier's performance, but the measured specifications speak for themselves.

To understand how the SOA protection works, consider the top half, based on NPN transistor Q6 and diode D1 plus three resistors: 18kΩ, 820Ω and 220Ω.

In normal operation, the voltage across the 0.22Ω emitter resistor of Q5 is less than 0.6V. Ignoring the extra resistors for now, this means that Q6 is biased off and has no effect.

Under fault conditions, the voltage across the 0.22Ω resistor increases to the point that Q6 starts to switch on. This diverts current from the base of driver transistor Q4 to the output, starving the driver of base current.

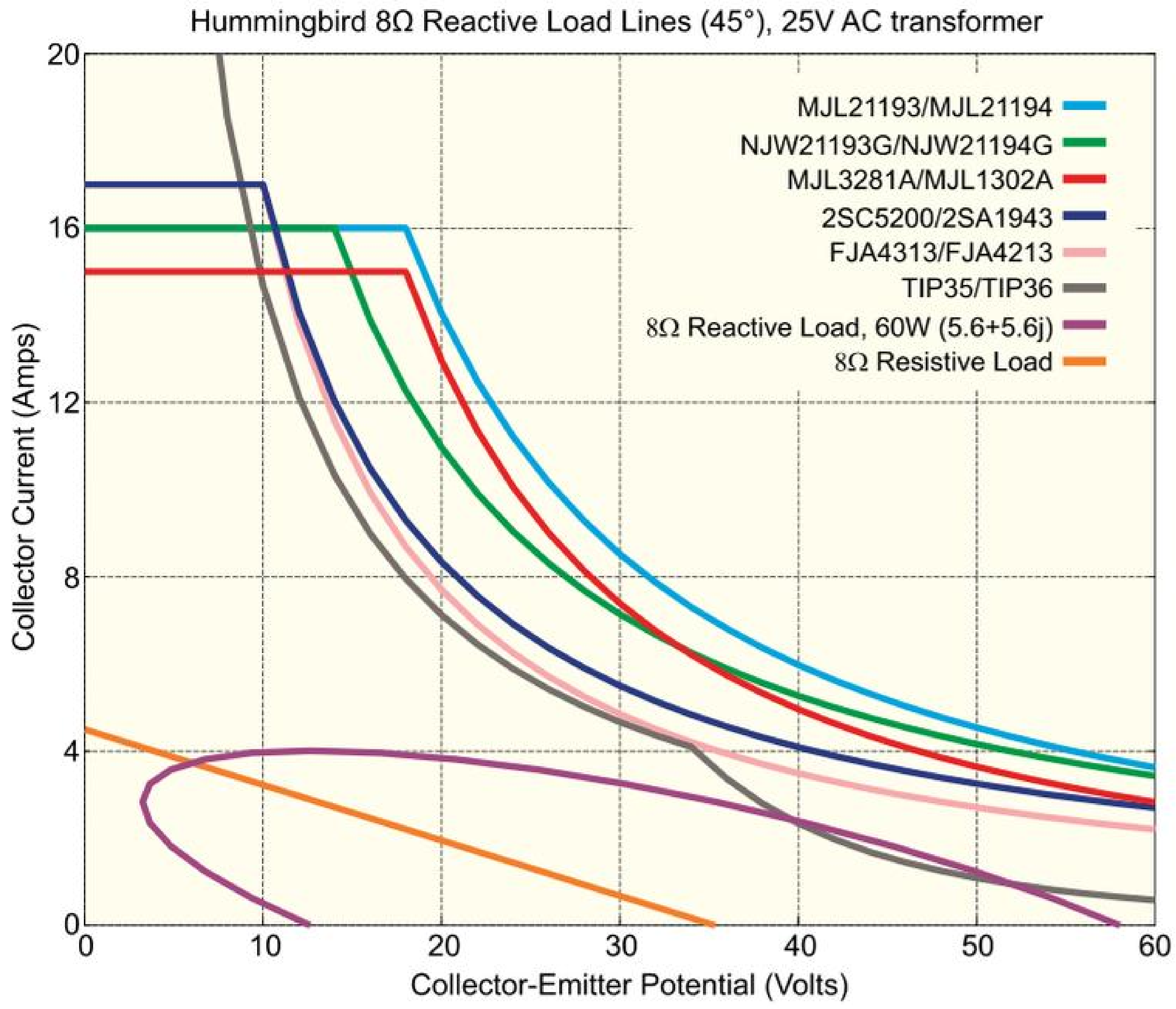


Fig.9: SOA curves for all the output devices you can use in the Hummingbird, plus load lines for 8Ω purely resistive and 45° reactive loads (representing a worst-case loudspeaker). This shows that all the output devices are safe for driving such loads with the recommended supply voltages, except perhaps the TIP35/36, so it's probably best to avoid those if possible.

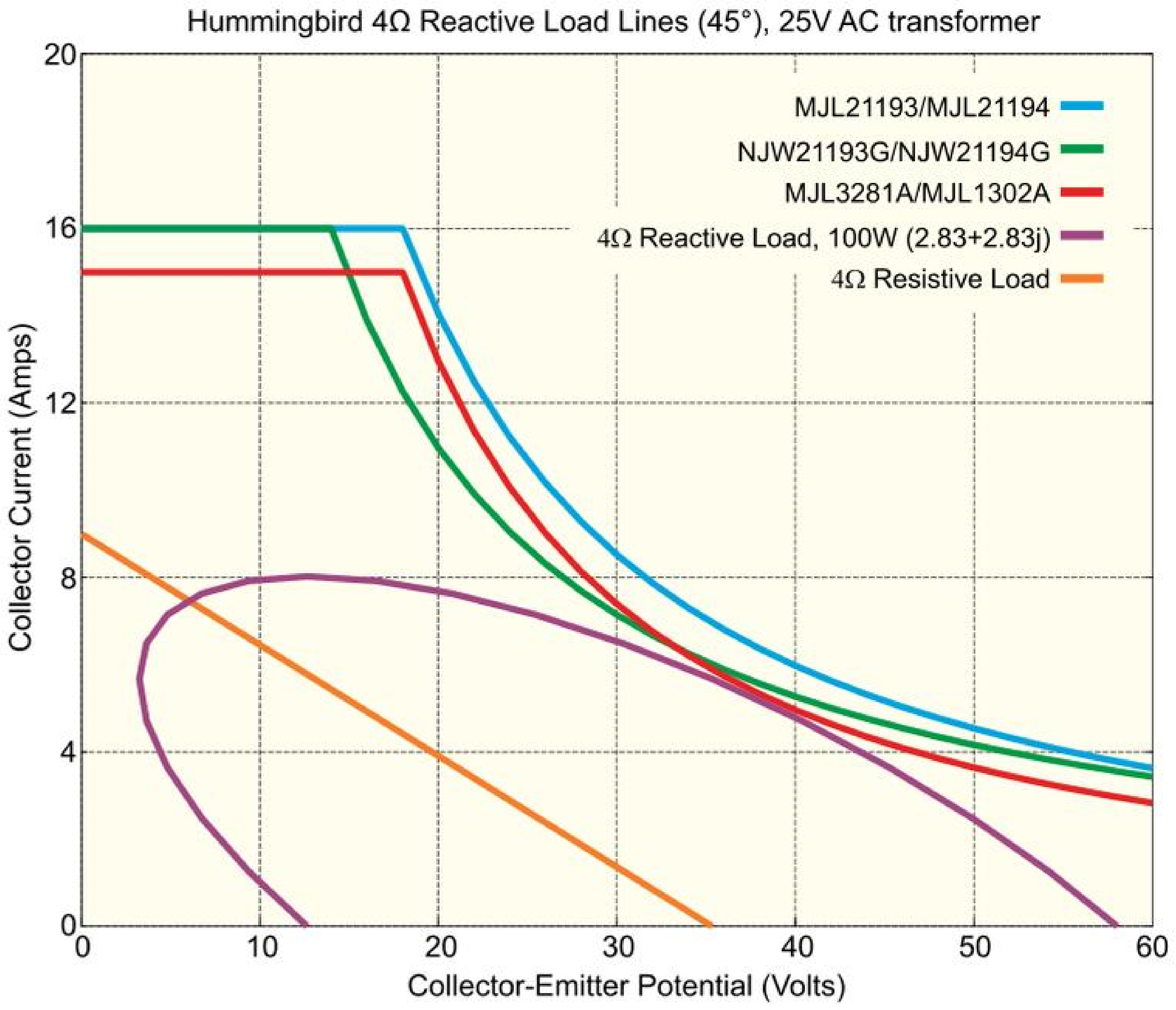


Fig.10: a similar plot to Fig.9 but this time, the load lines are for 4Ω resistive/reactive loads and we've eliminated those output devices that we don't recommend for driving 4Ω loudspeakers. All three options are pretty safe; the MJL3281A/MJL1302A pairing comes pretty close to the reactive load line, but the SOA protection circuitry is there to save the day if necessary.

This, in turn, starves the output device of base drive until the output current reduces to the point that Q6 is no longer switched on so hard.

This creates a local feedback loop that limits the output current, thus protecting the output stage. Diode D1 is included so that the opposing current protection circuit is not reverse-biased by heavy output loads.

In the absence of the three extra resistors, Q6 would switch on at an output current of about 3A (0.6V across a 0.22Ω resistor). This is too early, so to allow more current, the 820Ω and 220Ω resistors form a voltage divider with a division ratio of 0.21. Thus, a current of about 13A through the emitter resistor is required to turn the over-current protection on.

Without the 18kΩ resistor, the current limit will be the same regardless of the output voltage. Adding that resistor injects more current into the voltage divider formed by the other two resistors, so that at low output voltages, more current is injected, and the current limit kicks in earlier.

This results in the SOA protection being 'sloped' to fit the SOA of the output devices, and allows more current at high output voltages, because the voltage *across* the devices is lower. Thus they dissipate less power for the same current.

Output device selection

The pinout of the output devices is very common. The *Hummingbird* delivers the measured performance with the parts specified, but we have checked that the amplifier works properly with a range of other output transistors. You do need to change the SOA protection resistor values, though, as per Table 1. You also have options for the driver transistors (Table 2) and VAS transistor (Table 3).

Construction

All parts are through-hole, and they fit on the 64 x 88mm, double-sided PCB coded 01111211, shown in Fig.13 and availabel from the *PE PCB Service*. The parts are closely spaced but not too tight. We have kept the pad sizes generous to make soldering easier.

Before we continue, we strongly advise you to use transistors from a reputable supplier. There are cheap transistors on internet auction/sale sites. Do not be tempted by these. Fakes are prolific, even in surprisingly simple devices. All the devices recommended for this amplifier are available at reasonable prices from major suppliers.

Start by fitting all the small resistors and diodes – make sure the orientations of the diodes match what's shown in Fig.13 and on the PCB silkscreen. Follow with the trimpot, orienting its adjustment screw as shown. This is

Table 1 – alternative output transistors

NPN output	PNP output	SOA protection resistors			Comments and limitations	Status
NJW21194G	NJW21193G	18kΩ	820Ω	220Ω	Performance as presented	Verified
MJL21194	MJL21193	22kΩ	750Ω	220Ω	Performance as presented; THD <0.001% at 1kHz with MPSA42 VAS	Verified
FJA4313 or 2SC5242	FJA4213 or 2SA1962	22kΩ	470Ω	270Ω	Limit to 25V AC transformer if driving difficult 4Ω loads	Verified
2SC5200	2SA1943	18kΩ	560Ω	220Ω	Performs as specified	Verified
MJL3281A	MJL1302A	18kΩ	820Ω	220Ω		Not checked
TIP35B/C	TIP36B/C	27kΩ	1kΩ	390Ω	Limit to 25V AC transformer, prefer 8Ω load. Surprisingly good performance	Verified
TIP3055	TIP2955	12kΩ	680Ω	270Ω	Limit to 25V AC transformer and 8Ω load	Not checked

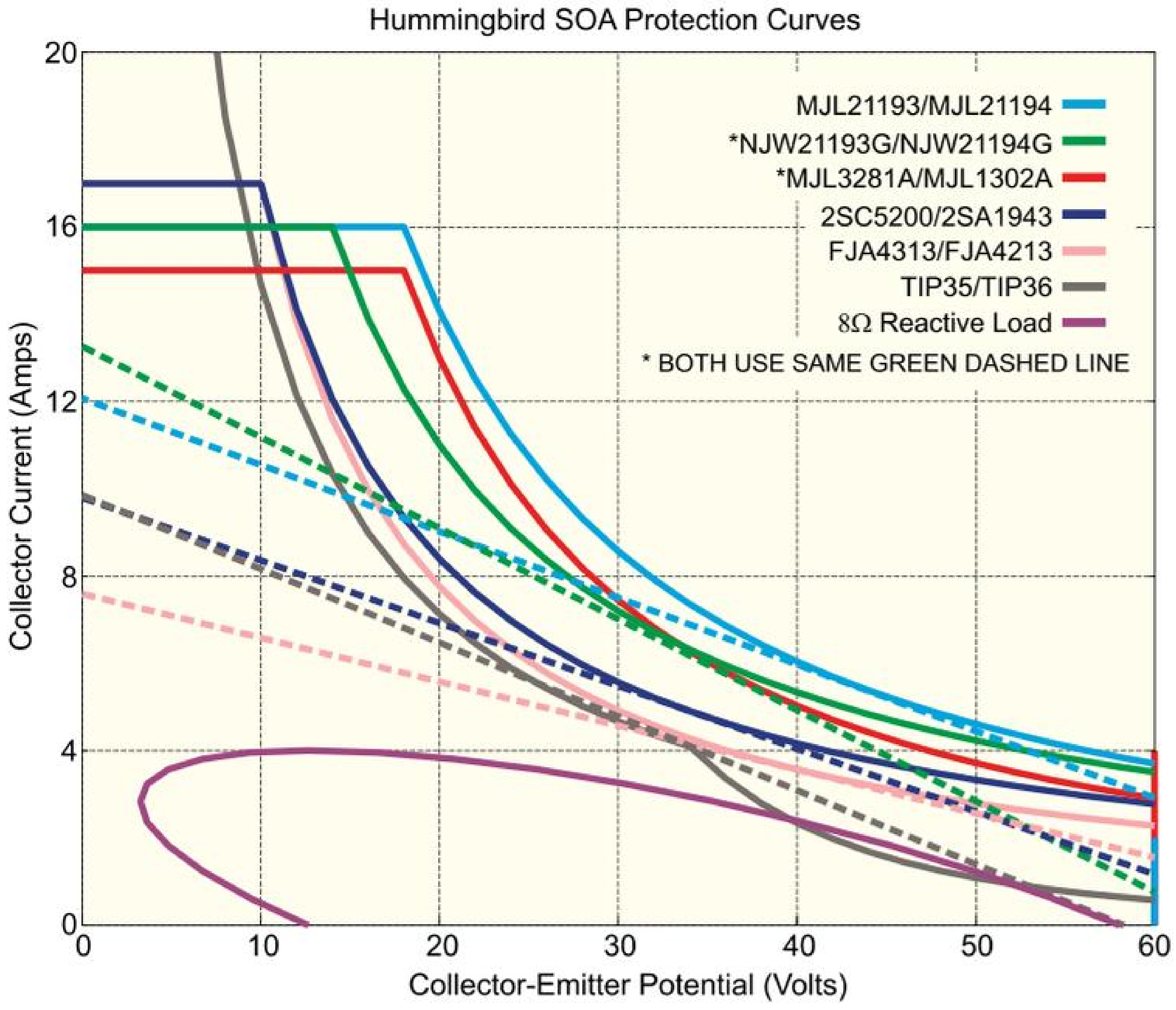
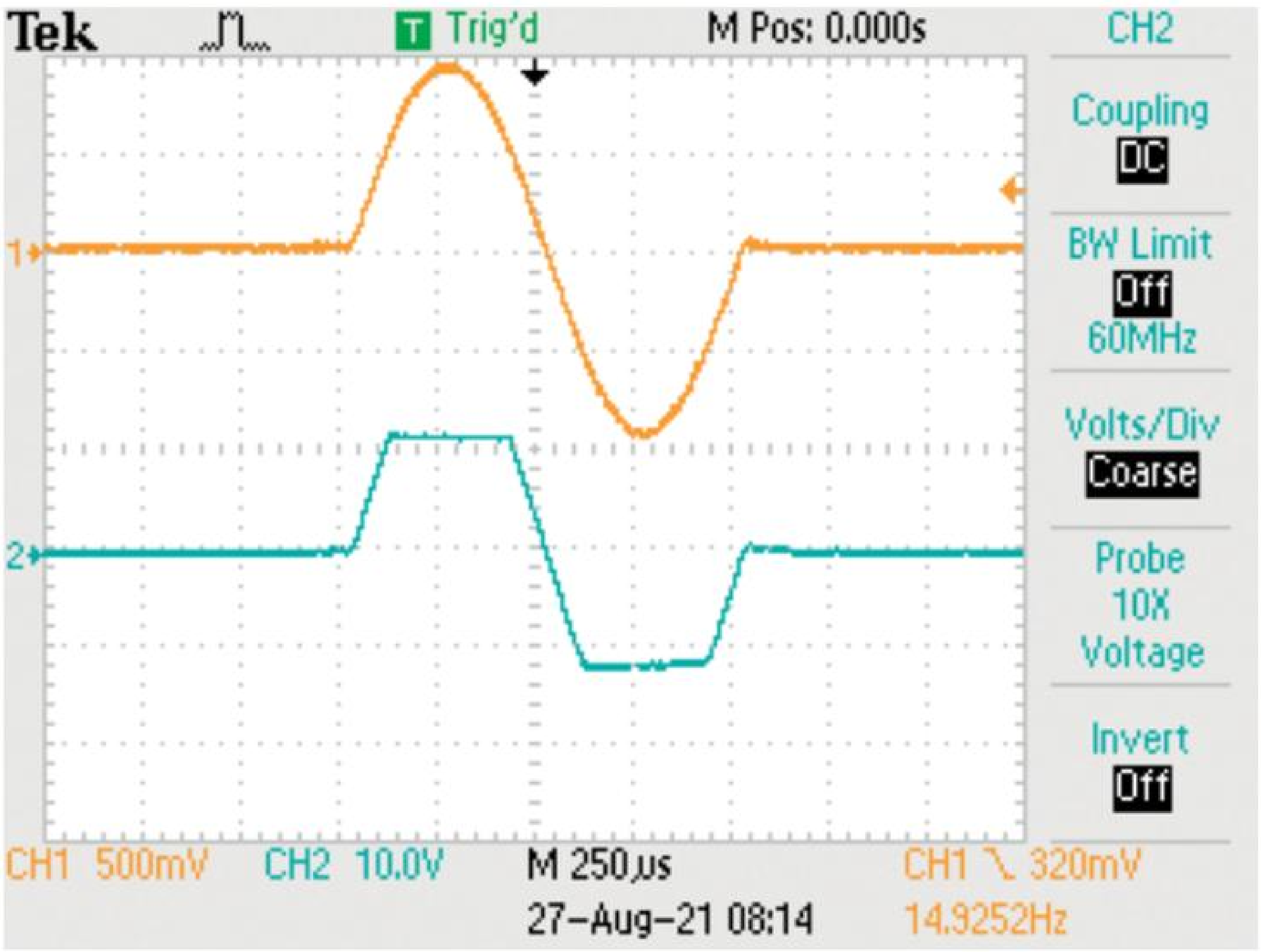


Fig.11: this shows all the output transistor SOAs again, as well as the SOA protection lines (dashed). While the protection lines are straight, they're positioned to stay below the SOA curves in almost all cases, so the amplifier can't drive the transistors outside of their SOA curves. The SOA protection lines for the NJW21193G/NJW21194G and MJL3281A/MJL1302A are identical (green dashed line) since, despite being different curves, they cross over at a critical point.

Fig.12: we deliberately overdrove the amplifier by connecting its output across a load of just 1Ω and fed it with a single sinewave pulse. This causes the output transistors to deliver so much current that it triggers the SOA protection circuitry. You can see from the bottom trace how it limits the output voltage/current to protect the transistors.



critical because we need to be able to set the quiescent current to a minimum before the module is first powered up.

Next, mount the input and output connectors. We have used parts with the common 5/5.08mm spacing on these (except the input, a 2.54mm-pitch header).

You should consider how you will mount the modules before choosing either screw terminals or pluggable connectors. Access to a screw terminal may be obstructed in some arrangements, so in that case, use pluggable connectors.

Now install all the non-polarised capacitors. Fit the MKT parts close to the PCB. Ensure you use a 100V-rated device for the 220pF capacitor.

Follow with the 5A fuses and their clips. We find it easiest to put the fuses in their clips and then solder that as an assembly to the PCB. This ensures everything is well-aligned.

Fit the electrolytic capacitors next, noting that they must all be installed with their + (longer) lead to the left when the PCB is oriented with the output devices at the top. Ensure that you have adequate voltage ratings on these parts (ie, at least what is specified in the parts list).

Now install the TO-92 transistors. It is worth finding matched pairs for Q7 and Q8 and also Q9 and Q10, if you can. To do this, check the h_{FE} figures of a handful of each type. Select pairs that have reasonably similar h_{FE} measurements; within 10% is fine. Also, try selecting pairs that have high h_{FE} figures compared to the others.

With the BC549 and BC556, an h_{FE} figure below 100 is cause to throw the part in the bin, although such a low reading is rare indeed.

Now is a good time to mount the remaining resistors. The only ones that get warm are the 0.22Ω output stage emitter resistors, and that's only when delivering full-power sinewaves from the amplifier, which will not happen with musical material. But it is still good practice to mount these a few millimetres proud of the PCB.

The PCB will accept standard 5W cast resistors, but we liked the look and fit of some smaller resistors from Mouser (see the parts list). They need to have a rating of at least 3W in this application, so 5W is quite conservative.

Making inductor L1

The output inductor is made from 0.8mm enamelled copper wire (ECW) as follows:

1. Find a mandrel that is a bit over 10mm in diameter and has a slight chamfer so that once complete, you can push the inductor off. We used a large 'Sharpie' brand permanent marker.
2. Put masking tape around this mandrel but ensure the sticky side is facing *outwards*.
3. Place a bend in the enamelled copper wire (ECW), 30-40mm from the end, and wind nine turns onto the masking tape.

Table 2 – alternative driver transistors

NPN driver	PNP driver	Comments	Status
MJE15032	MJE15033	As specified (MJE15034 and MJE15035 have not been tested but should be similar)	Verified
MJE15030	MJE15031	These perform well with 8Ω and 6Ω loads. At 3Ω, distortion increases faster than the specified devices, but they are still a fair choice	Verified
TIP31B/C	TIP32B/C	Performs close to specifications. With 3Ω loads, distortion increases faster than the specified devices, but they are still a fair choice	Verified
BD139	BD140	Install in opposite orientation (ECB vs BCE pinout). The –16 gain group parts are the best choice. Limit to 25V AC transformer	Verified
MJE350	MJE340	Install in opposite orientation (ECB vs BCE pinout). Not ideal. Marginal on maximum current. Limit to 8Ω and 25V AC transformer	Not checked

Table.3 – alternative VAS transistors

NPN VAS	Comment	Status
KSC3505DS	As specified	Verified
BF469	As specified	Verified
BD139	Slightly elevated distortion, but a surprisingly good performer – rumour has it that there are many 'types' of BD139, so 'your mileage may vary'.	Verified
MPSA42	Pinout is different. Measured THD <0.001% at 1kHz with MJL21193/4 output transistors. More negative rail 'sticking' than KSC3505DS, but not excessive	Verified

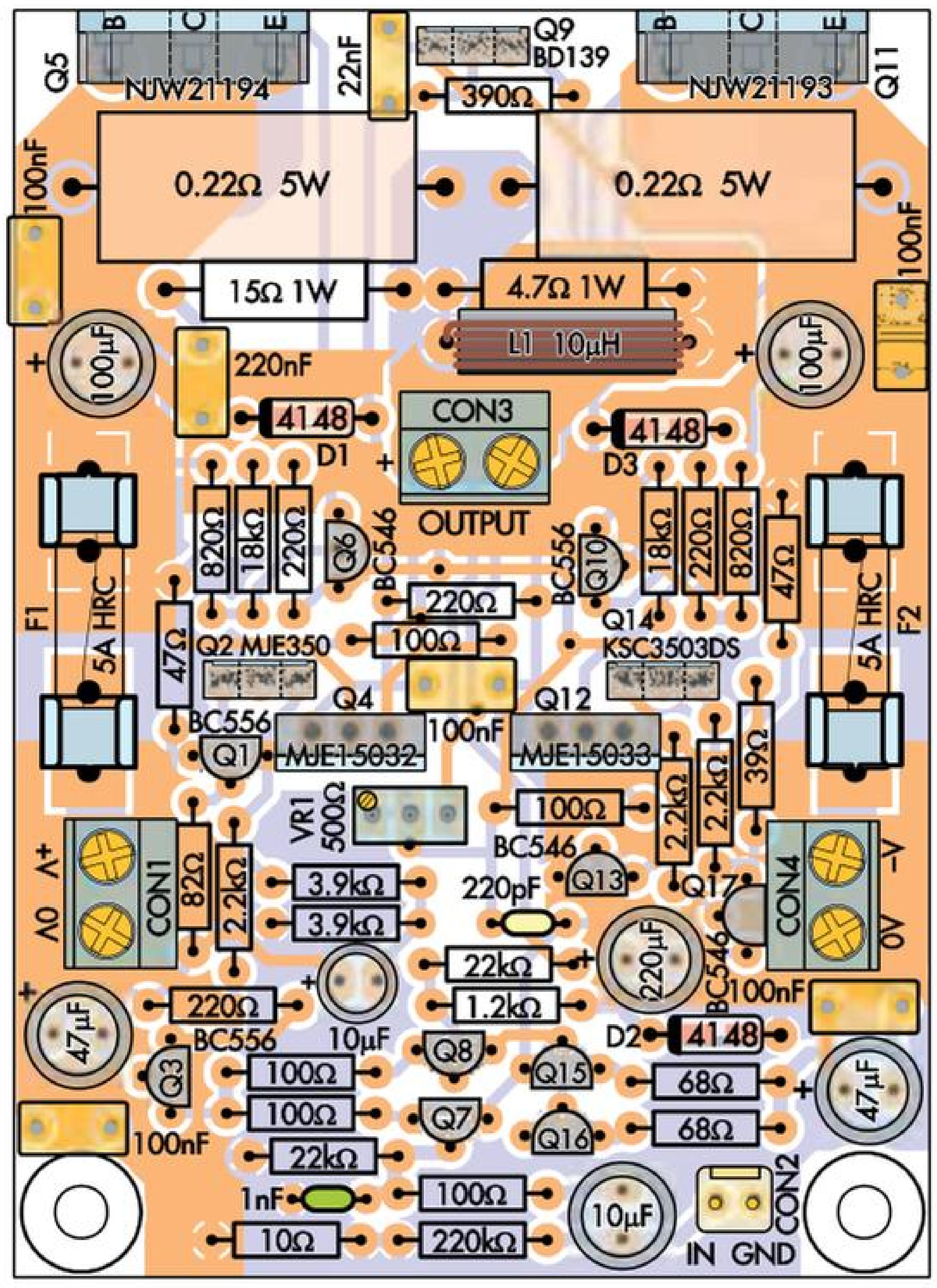

Q5
B C E
NJW21194
22nF
Q9
BD139
390Ω
B C E
NJW21193
Q11
100nF
0.22Ω 5W
0.22Ω 5W
100nF
15Ω 1W
4.7Ω 1W
L1 10μH
100μF
220nF
100μF
4148
D1
CON3
OUTPUT
4148
D3
820Ω
18kΩ
220Ω
Q6
BC546
BC556
Q10
18kΩ
220Ω
820Ω
47Ω
F1
5A HRC
47Ω
Q2 MJE350
220Ω
100Ω
Q14
KSC3503DS
5A HRC
F2
BC556
Q1
Q4
MJE15032
100nF
Q12
MJE15033
2.2kΩ
39Ω
VR1
500Ω
100Ω
BC546
A+
0V
CON1
82Ω
2.2kΩ
3.9kΩ
3.9kΩ
220pF
Q13
Q17
BC546
220μF
CON4
–V
0V
47μF
220Ω
BC556
10μF
Q3
22kΩ
1.2kΩ
100nF
D2
4148
100Ω
Q8
Q15
68Ω
47μF
100Ω
Q7
Q16
68Ω
100nF
22kΩ
1nF
100Ω
10μF
CON2
10Ω
220kΩ
IN GND

Fig.13: building the Hummingbird is straightforward; fit the components to the PCB as shown here. Watch the orientations of all diodes, transistors and electrolytic capacitors. For the TO-220 and TO-126 devices, the metal tabs face as shown here (if your TO-126 device lacks a metal tab, it would typically be opposite the side with writing on it). Don't forget that if any of your transistors are substitutes for the recommended devices, they will have different part codes than those shown here – see Tables 1-3.

4. Put a few drops of super glue on the ECW. Don't worry if it gets on the masking tape, but you probably don't want to get it on your mandrel!
5. Give this a minute to set, then wind another layer on top of the first nine turns. You might only be able to get eight more in; that is OK. Add more superglue and again let it to set.
6. Add the final winding of nine turns over that and glue again.
7. Push the inductor off the mandrel. Don't be scared to give it a solid push.
8. Tease the masking tape from inside the inductor; we used long-nose pliers. Then we added some extra super glue.
9. Trim the ends, scrape the enamel off them and mount it to the PCB above the 4.7Ω resistor as shown.

Finishing construction

Now fit the remaining transistors: solder Q2, Q4, Q12 and Q14 directly to the PCB. The BD139, NJW21193 and NJW21194 devices that mount on the main heatsink (Q5, Q9 and Q11) come last.

Before proceeding, check your mounting arrangements and ensure that you load these at the right height for mounting on the main heatsink. The best way to mount these transistors to the heatsink is with the insulating kits and machine screws. Bend their leads to fit the board and then solder them. If you can, tap the heatsink to accept the screws, otherwise, drill through between fins and use long screws/nuts.

Adjustment and testing

It is critical that the bias adjusting potentiometer is set to maximum resistance so that the initial bias current is very low. Do this by turning it clockwise a minimum of 20 turns. Check with a multimeter that there is close to 500Ω between the cathode (striped end) of diode D3 and the right-hand end of the 390Ω resistor, just to the left of Q11.

Do this now – if you forget, you might blow the fuses when you power it up, and fuses aren't always fast enough to protect semiconductors.

You can do some initial testing without mounting the amplifier to a heatsink. This test will check that the amplifier is operational. Remove the 5A fuses from the board and install the test (blown) M205 fuses with 10Ω 5W resistors soldered across them. We refer to these as 'safety resistors'.

Connect a voltmeter between the output and ground, set to a 200V range (or similar). Connect another voltmeter across one of the 10Ω resistors, set to a 20V range or similar. If you only have one meter, run an initial check monitoring the output voltage only.

With the input to the module disconnected, apply power. Anything over about ±15V is fine. If you can, set the current limit on the power supply to about 100mA.

Check that the output voltage settles to 0V ±50mV. We built 14 test units, and all were within that range. Also check that the voltage across the 10Ω safety resistor is less than 1V.

If either of these tests fail, immediately power it off and check for the cause.

Have you got the bias pot set at the right end of its travel? Are all the capacitors in the right way around? Do you have a signal feeding the input? If so, disconnect it. Are all the transistors and diodes in the right places and the right way around? Check that those output devices are in the right spot!

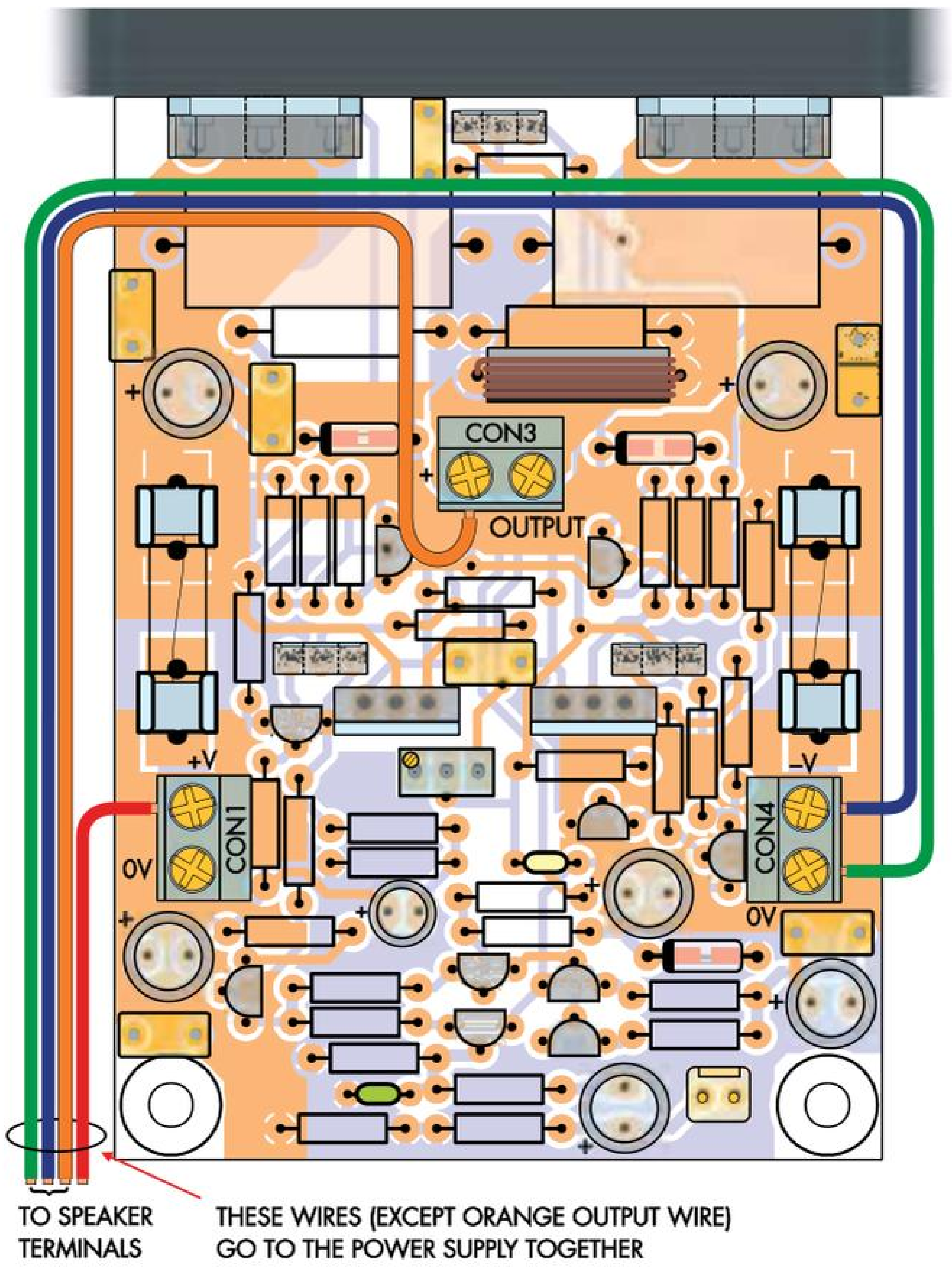

CON3
OUTPUT
+V
CON1
0V
–V
CON4
0V
TO SPEAKER TERMINALS
THESE WIRES (EXCEPT ORANGE OUTPUT WIRE) GO TO THE POWER SUPPLY TOGETHER

Fig.14: route the wiring to each module like this to ensure you get the stated performance. Current flowing through these wires will cause magnetic fields, which affect the operation of components on the amplifier. Routing the cables this way keeps those magnetic field strengths low. Once you've run them, use cable ties and cable clamp to hold them in place and keep everything neat.

Parts List – Hummingbird (for one amplifier)

1 double-sided PCB coded 01111211, 64 x 88mm, avavaiable from the *PE PCB Service*
1 split rail power supply delivering ±20V to ±40V DC (eg, 15-28V AC mains transformer, bridge rectifier, filter capacitors, mains socket, mains-rated wiring, heatshrink tubing etc) – see Fig.15
3 2-way 5/5.08mm pitch mini terminal blocks (CON1, CON3, CON4)
1 2-way polarised/locking pin header (CON2)
4 M205 fuse clips (F1, F2)
2 5A 5mm ceramic fuses (F1, F2)
1 1m length of 0.8mm diameter enamelled copper wire (L1)
1 500Ω vertical or side-adjust multi-turn trimpot (VR1)
2 TO-3P insulating kits (washers and bushes)
1 TO-126 insulating kit (washer and bush)
3 M3 x 25mm panhead machine screws
3 flat washers to suit M3 screws
3 crinkle washers to suit M3 screws
3 M3 hex nuts
2 blown 5mm fuses (for testing, or purposefully blow 100mA fuses)
1 heatsink, type depending on intended application (we used one Altronics H0545 for six modules)
1 small tube of superglue
1 5cm length of masking tape

Semiconductors
5 BC556 65V 100mA PNP transistors, TO-92 (Q1, Q3, Q7, Q8, Q10)
1 MJE350 300V 500mA PNP transistor, TO-126 (Q2) **[Altronics Z1127, Jaycar ZT2260]**
1 MJE15032G or MJE15034G 250V/350V 8A NPN transistor, TO-220 (Q4) **[element14 9556621, Digi-Key MJE15034GOS-ND, Mouser 863-MJE15032G]**
1 NJW21194G or MJL21194 250V 16A NPN transistor, TO-3P (Q5) **[Jaycar ZT2228, element14 2535656, Digi-Key NJW21194GOS-ND, Mouser 863-NJW21194G]**
3 BC546 65V 100mA NPN transistors, TO-92 (Q6, Q13, Q17)
1 BD139 80V 1A NPN transistor, TO-126 (Q9) **[Altronics Z1068, Jaycar ZT2189]**
1 NJW21193G or MJL21193 250V 16A PNP transistor, TO-3P (Q11) **[Jaycar ZT2227, element14 9555781, Digi-Key NJW21193GOS-ND, Mouser 863-NJW21193G]**
1 MJE15033G or MJE15035G 250V/350V 8A PNP transistor, TO-220 (Q12) **[element14 9556630, Digi-Key MJE15035GOS-ND, Mouser 863-MJE15033G]**
1 KSC3503DS 300V 100mA NPN transistor, TO-126 (Q14) **[element14 2453955, Digi-Key KSC3503DS-ND, Mouser 512-KSC3503DS]**
2 BC549 30V 100mA NPN transistors (Q15, Q16)
3 1N4148 75V 250mA small signal diodes (D1-D3)

Capacitors
1 220µF 25V electrolytic **[Altronics R5144, Jaycar RE6324]**
2 100µF 50V 105°C electrolytic **[Altronics R4827, Jaycar RE6346]**
2 47µF 50V low-ESR electrolytic **[Altronics R6107, Jaycar RE6344]**
1 10µF 50V low-ESR electrolytic **[Altronics R6067, Jaycar RE6075]**
1 10µF 50V non-polarised electrolytic **[Altronics R6560, Jaycar RY6810]**
1 220nF 63V MKT **[Altronics R3029B, Jaycar RM7145]**
5 100nF 63V MKT **[Altronics R3025B, Jaycar RM7125]**
1 22nF 63V MKT **[Altronics R3017B, Jaycar RM7085]**
1 1nF 63V MKT **[Altronics R3001B, Jaycar RM7010]**
1 220pF 100V NP0/C0G ceramic **[eg, element14 2860112, Digi-Key 445-173535-1-ND, Mouser 810-FG28C0G2A221JNT6]**

Resistors *(all ¼W+ 1% metal film axial unless otherwise stated)*
1 220kΩ
2 18kΩ
3 2.2kΩ
2 820Ω
4 220Ω
5 100Ω 0.5W or 0.6W 1% metal film
2 68Ω
1 39Ω
1 10Ω
1 4.7Ω 1W
2 22kΩ
2 3.9kΩ
1 1.2kΩ
1 390Ω
1 82Ω
2 47Ω 0.5W or 0.6W 1% metal film
1 15Ω 1W
2 10Ω 5W 10% **(for testing)**
2 0.22Ω 5W 5% **[element14 1735119, Digi-Key BC3440CT-ND, Mouser 594-AC050002207JAC00]**

Altronics kit
Australian company Altronics offer a kit for this project, code K5158, at around £35 per module PLUS p&p – see: www.altronics.com.au

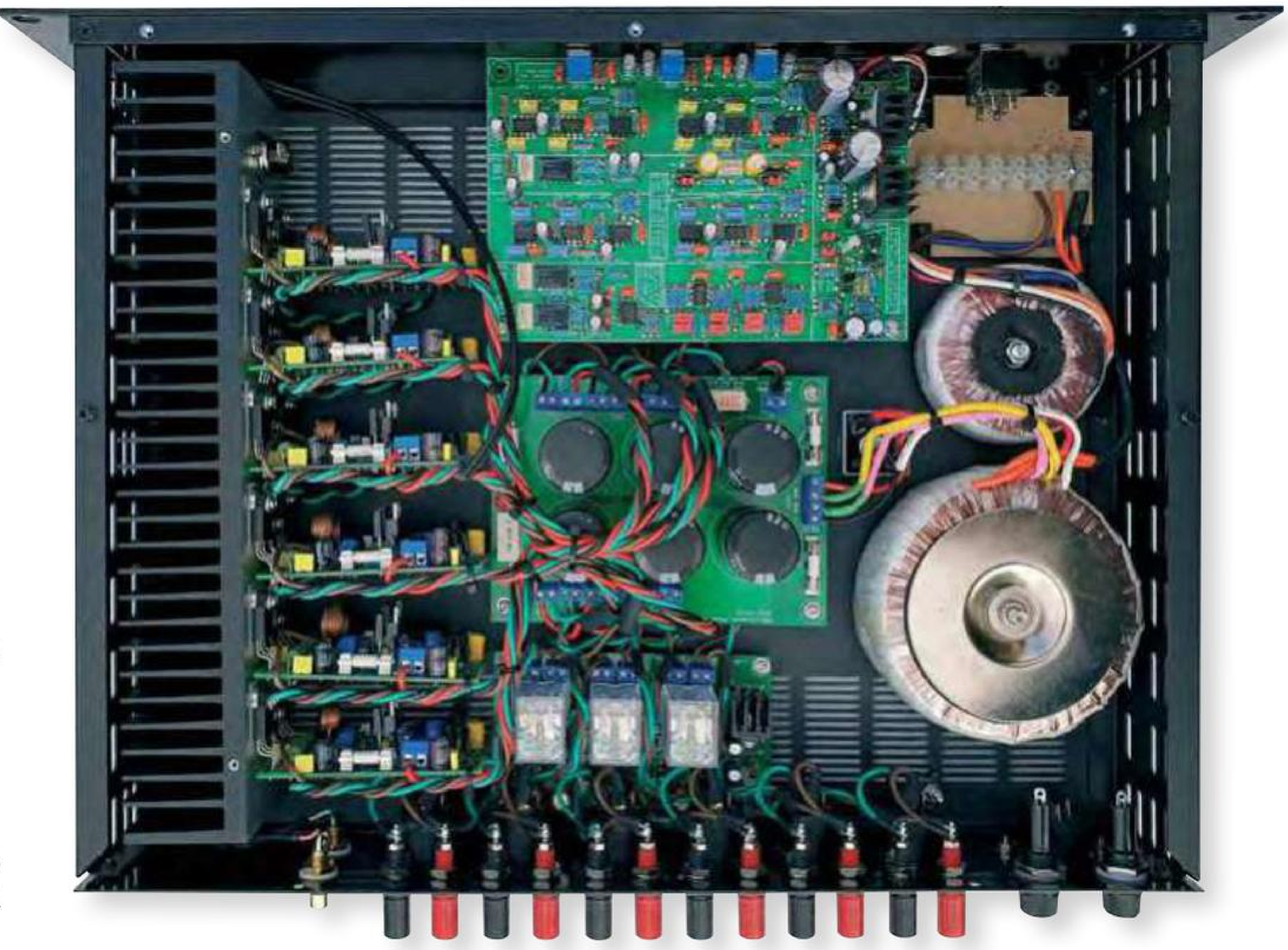
Is your power supply delivering both positive and negative rails, and do you have the ground connected?

Setting the bias

This requires the amplifier to be mounted to a heatsink with appropriate insulators for the output devices and V_{BE} multiplier transistor. Power it up and adjust the bias by turning potentiometer VR1's screw anticlockwise while watching the voltage across the 10Ω resistor. Nothing will happen for quite a few turns; then, the bias current will rapidly increase. Adjust this to achieve 500mV across the resistor.

Allow this to settle and readjust. It will take a while to settle; depending on your mounting arrangement this should be done with the full supply voltage applied (ie, the final voltages you intend to use).

Re-install the 5A fuses, and you are ready to go. You can check the bias



The Amplifier can be cleanly mounted to a 75mm heatsink as shown above. The SOA protection resistors are missing as we wanted to compare the performance with and without them. After which you can daisy-chain them together to form a larger system such as a six channel setup shown adjacent. This setup was mounted in a 2U rack case.

later by measuring the voltage across the 0.22Ω resistors; you should see 10mV across each. If you're mounting multiple modules on a heatsink sideways as we did, the side-adjust style trimpot specified makes this quite easy.

Installation

To minimise distortion to the levels presented requires careful attention to layout and the power supply wiring. Our recommended wiring layout per module is shown in Fig.14, and the recommended power supply configuration is shown in Fig.15.

The wiring from the main supply capacitors should have the positive, negative and ground wires twisted together. The output should fold back toward the output devices, run parallel to the 0.22Ω output resistors, then follow the power wires.

The output wire should follow the power wires back past the power supply and pick up a ground wire, minimising the loop area created, then run as a pair from there to the speaker terminals (see above).

Ensure that the power supply has a 'star earth point' from which you connect to the input ground, the amplifier ground and the speaker output ground. Also check that the way you connect the rectifier and its ground connection to the capacitors does not inject noise onto your star earth point. Connect the input shielded cable screen to the star point.

Make sure all connections are secure and have low resistance; poor connections can easily double the distortion levels, or more. We found this measuring a batch of modules we built to verify our results; we had to tighten the connections to achieve consistent results.

Getting the most out of it

We expect this module to find use where a small, low distortion, rugged and reasonably priced multi-channel amplifier is required. As these modules will fit on a 75mm heatsink, many of them can be mounted vertically in a 2U rack case.

Our original application for this amplifier was to provide six channels for a stereo system using three-way loudspeakers with active crossovers. With two channels for subwoofers, two for mid-range two for tweeters, we expect the maximum continuous power to be 60W on each subwoofer channel, possibly half this for the mid and a tiny fraction of this on the high.

As a result, a power supply based on a 300VA transformer will be more than enough for all six channels. Even a 160VA transformer might cut it if you don't plan on driving it especially hard. If your application calls for high power levels, there are more appropriate options, such as the *SC200 Amplifier Module* (see *PE*, January to Match 2018). You could use a pair of those for the low-frequency channels and the *Hummingbird* for the others.

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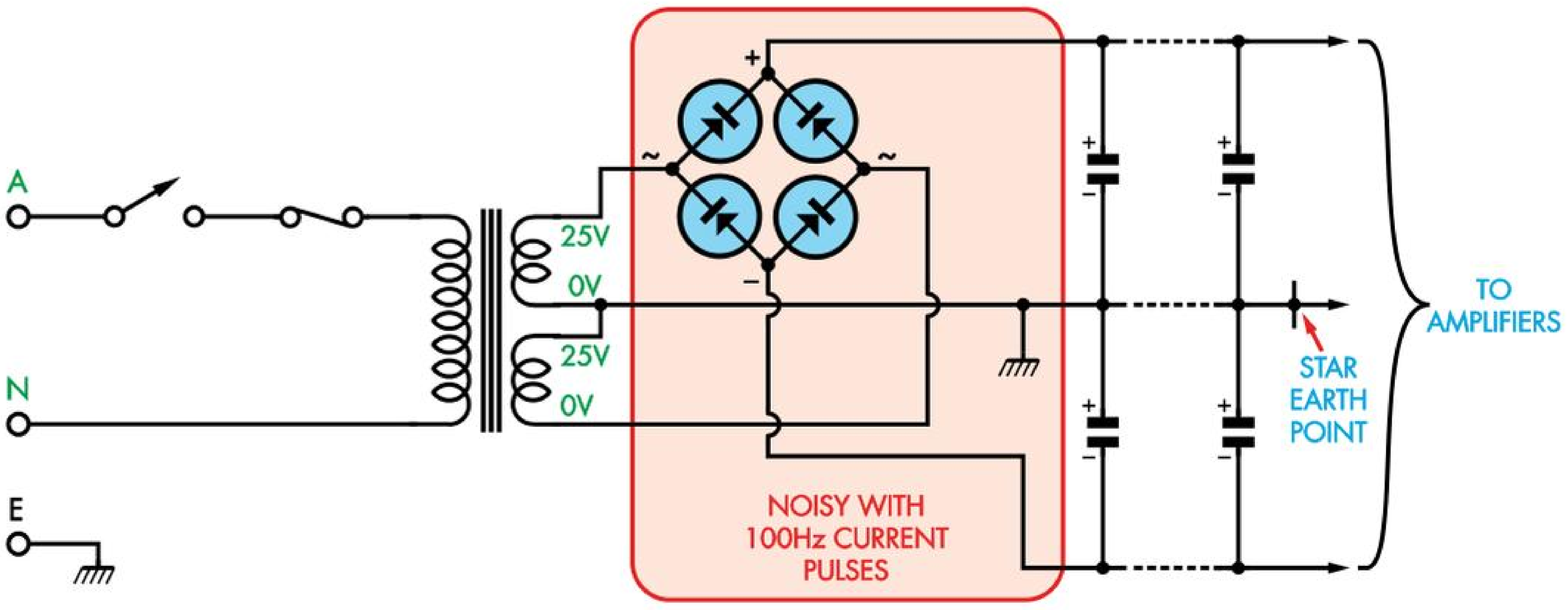

Fig.15: we've left the power supply for the Hummingbird somewhat open-ended, as it has pretty standard requirements. It just needs split DC rails without too much ripple, somewhere between ±20V and ±40V. The configuration above will produce around ±34V, which is right in the sweet spot and uses commonly available parts. Make sure your filter capacitors have a high enough voltage rating (above the highest expected peak DC voltage) and enough capacitance to 'hold up' the supply between 100Hz recharge pulses at the maximum sustained output power you're expecting. Generally, you will need at least a few thousand microfarads per rail; ideally, at least 10,000µF per rail for multiple amplifier modules.

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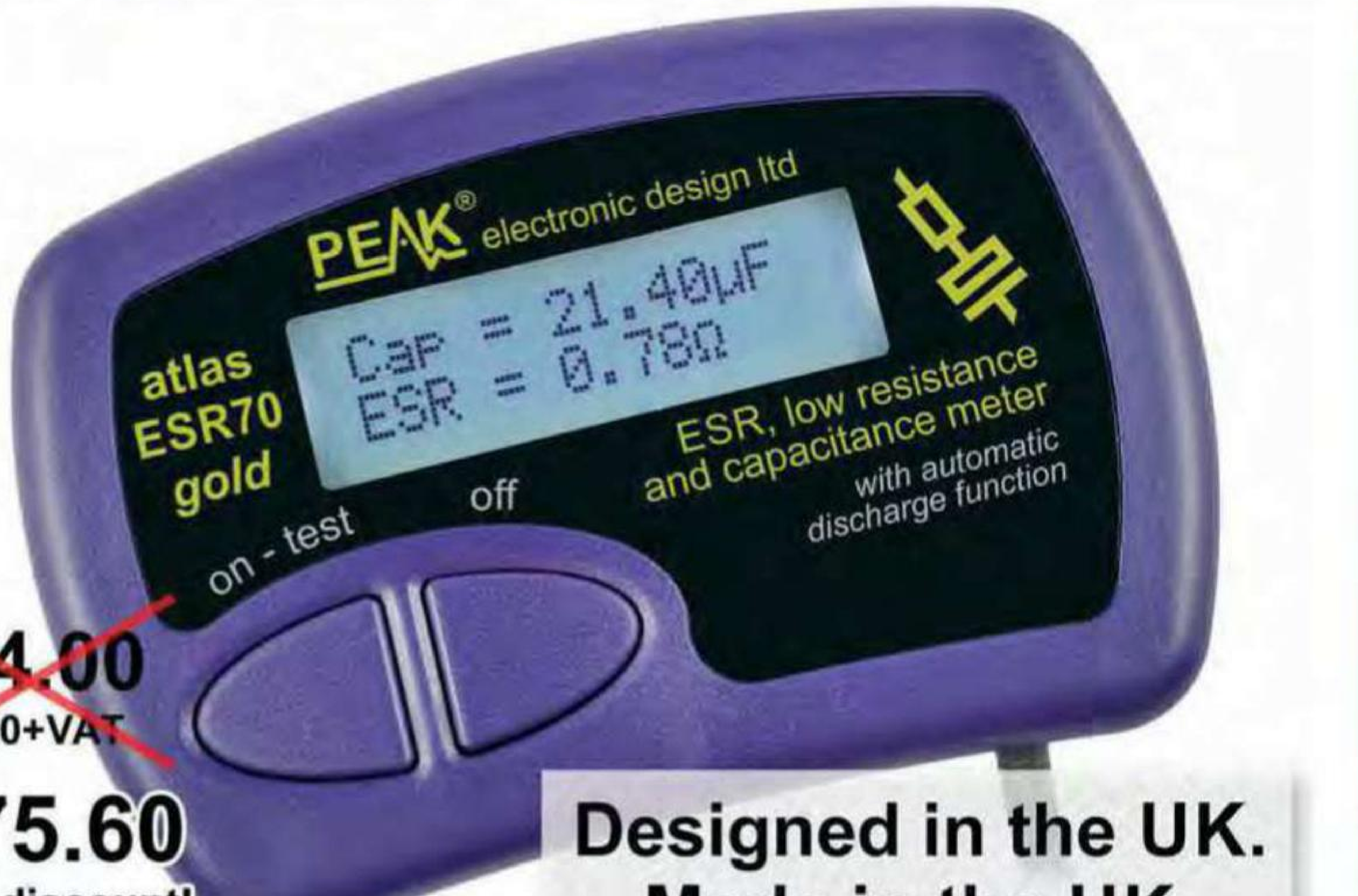
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Downstream Facing Ports
Upstream Facing Ports

Our USB Cable Tester, introduced last month, is ideal for going through piles of cables and sorting them out. It's also a great first step in diagnosing a faulty USB-connected device. It can perform continuity and short-circuit checks on practically any USB cable and will report problems such as high resistance in the power wires; a source of frustrating intermittent faults.

In the initial article last month, we described the reasoning and principles of operation behind the *USB Cable Tester*. Bristling with all the standard USB sockets, it will test and diagnose any cable with either a USB-C or USB-A (2.0 or 3.2) on one end and any of USB-C or USB-B (such as 2.0, 3.2, micro or mini) on the other end.

It will report whether the cable is suitable for power only, USB 2.0 or USB 3.2 operation (and indicate whether one or two SuperSpeed lanes are present). With USB 3.2 (which has replaced USB 3.0 and USB 3.1), each SuperSpeed lane consists of four wires, forming differential pairs in both (upstream and downstream) directions.

The unit scans every combination of wires among the upstream-facing and downstream-facing ports. It can tell you which wires are internally shorted or open circuit to help with diagnosis and repair.

The *USB Cable Tester* also runs pulses of up to 1A through the cable's power (VBUS and GND) wires to assess their ability to carry current under real-world conditions. The resistance and voltage drop is reported.

This feature will ferret out many cables that are causing intermittent problems. When devices such as portable hard drives mysteriously stop working, it's possibly due to their high-current needs being hampered by poor connections.

With this tool, you can weed out dodgy cables and choose the best ones for high-current applications. Now you can know for sure if it's the cable or the device that's causing problems.

The *USB Cable Tester* can also run tests when only one end of a USB cable is plugged in, and it does this for three reasons.

First, it verifies cables that are OTG (USB on-the-go) compatible, which short their GND and ID pins. This state indicates to a device that it should instead behave as a host. Since OTG cables are usually adaptors, their other end is typically a socket, so you can't plug in it at both ends.

The second reason is to help those who construct and repair cables. You can use it to check individual cable halves, mainly to ensure that there are no shorts between any conductors.

The third is perhaps the most important. That is to check that the very fiddly USB sockets have been correctly soldered to the PCB. It's a kind of self-diagnosis.

We will offer a different order of construction than usual to take advantage of this self-diagnosis feature.

PCB layout

The internal photos and the overlay diagram (Fig.3) show that the USB sockets all lie along one edge of the PCB. CON5, CON6 and CON8 are on a narrow neck without any surrounding components. That makes fitting those sockets easier.

The other sockets (CON3, CON4 and CON7) are near the relays and buck circuitry around Q3. Since these components are only needed for the power testing and not connectivity testing, we can fit those other components after confirming the USB sockets have been soldered correctly.

So, no components below the rows of resistors and above the sockets should be fitted until later, except for the two other surface-mounting parts, the 220mΩ resistor and the inductor L1. These are low in profile and can be fitted with the other surface-mounting parts to simplify the workflow.

Enclosure

Prepare the case lid as the first step because the LCD is needed to perform our initial diagnostic tests, and also we need to align all the parts to fit the LCD headers accurately.

Refer to the cutting diagram, Fig.4. The single 4mm hole at upper right is for access to pushbutton S1; we suggest reading the Options section below to determine if you wish to fit it (and thus whether this hole is needed).

It's essential that the opening for the LCD is centred horizontally to avoid the connecting header being skewed. We used a technique that requires a sharp hobby knife, pliers (preferably wide-nosed), a hacksaw or jigsaw and a drill.

You can use the bezel as a template, keeping in mind that the bezel will hide most imperfections in the top panel. Mark the edges of the hole on both sides; small holes drilled in the very corners of the cutout area will help to align the two sides.

Firmly score the rectangular cutout with the hobby knife against a straight edge. Take care with this, as a slip with a sharp knife can really hurt you!

Make a hole in the centre of the rectangle that's large enough to accept the saw blade, then use the saw to cut up to the scored edges. You'll need to make a number of these cuts around the edge to divide the rectangle into manageable pieces.

Then carefully flex the plastic to snap it along the score lines and break out the centre area in small sections. If the score lines are accurate, the result will have neat, precise edges. Use the hobby knife to lightly shave small pieces of plastic from the edges of the hole to enlarge the hole if necessary and to tidy up.

Another method is to drill a row of holes *inside* the periphery of the marked area to remove most of the plastic, then file the edges smooth until the LCD fits. This is slower but requires fewer tools.

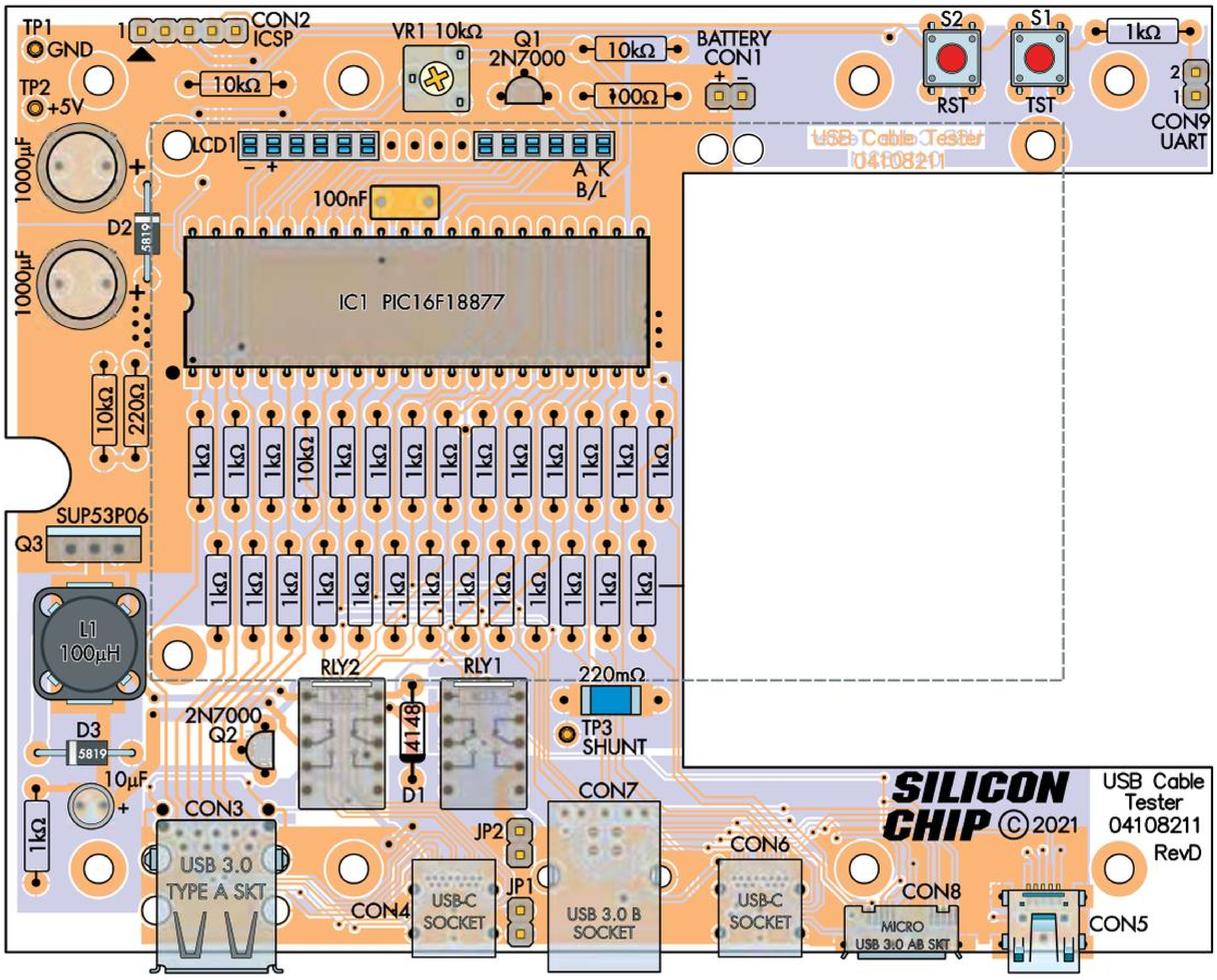
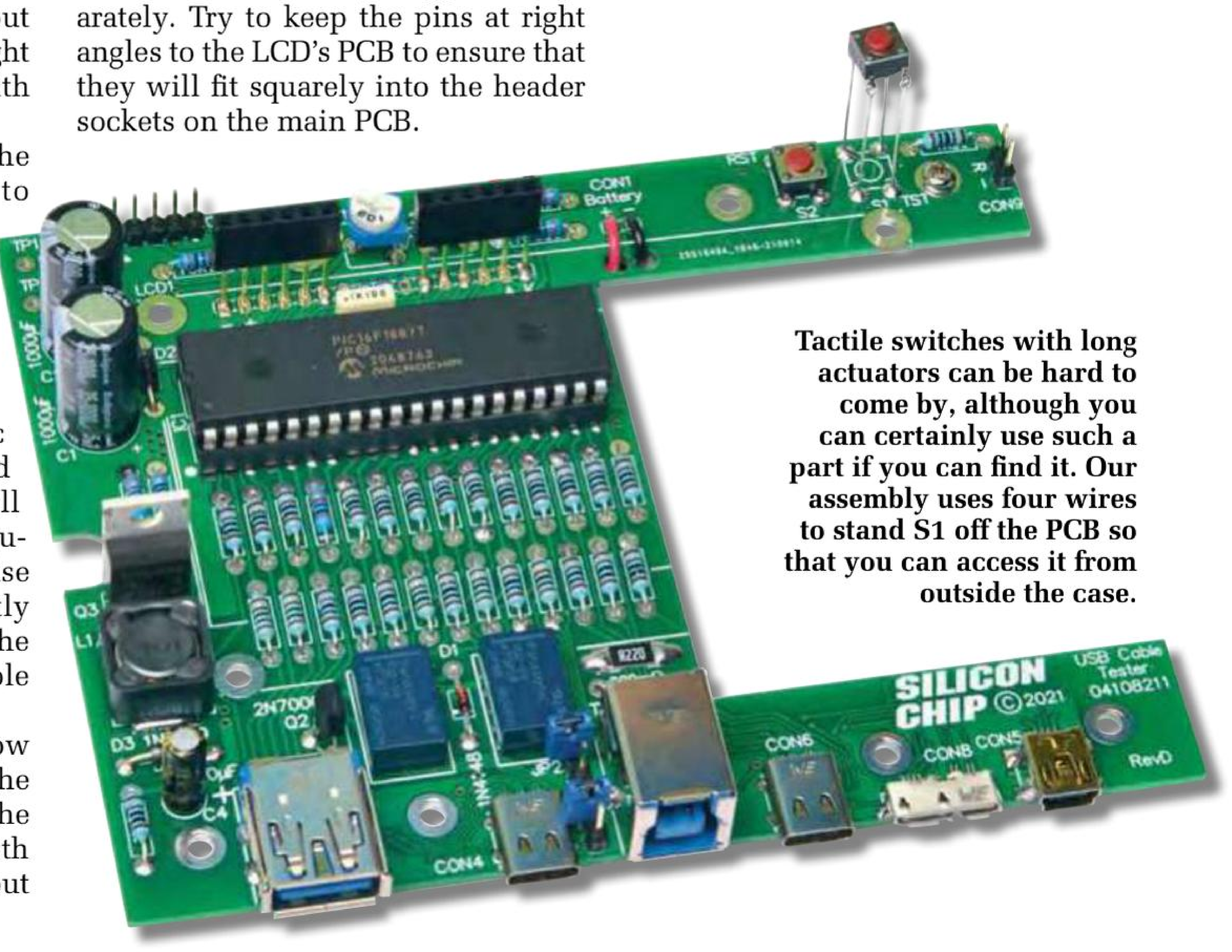

TP1
GND
TP2
+5V
CON2
ICSP
1
VR1 10kΩ
Q1
2N7000
10kΩ
100Ω
BATTERY
CON1
S2
S1
RST
TST
1kΩ
CON9
UART
2
1
LCD1
A K
B/L
USB Cable Tester
04108211
1000μF
1000μF
D2
5819
100nF
IC1 PIC16F18877
10kΩ
220Ω
1kΩ
SUP53P06
Q3
L1
100μH
RLY2
RLY1
220mΩ
2N7000
Q2
4148
D1
TP3
SHUNT
D3
5819
10μF
CON3
USB 3.0
TYPE A SKT
CON4
USB-C
SOCKET
JP2
JP1
CON7
USB 3.0 B
SOCKET
CON6
USB-C
SOCKET
CON8
MICRO
USB 3.0 AB SKT
CON5
SILICON CHIP
©2021
USB Cable
Tester
04108211
RevD

Fig.3: the only parts that are somewhat tricky to fit are the USB sockets. Make sure that IC1, RLY1, RLY2, the diodes and MOSFETs are oriented as shown. Note that there is a single 10kΩ resistor among the rows of 1kΩ parts. The USB Cable Tester might still work if you mix this up, but it will drain the battery much more quickly. The six USB sockets are located along one edge of the PCB. It is important to fit USB-C socket CON4 before the relays and associated parts are mounted on the board, so you have decent access to its pins.

With the LCD in place, you can use it (or the bezel) to mark and drill the location of the four mounting holes.

If your LCD doesn't have a pin header fitted to its underside, solder it now. When the screen comes with a header, it's usually supplied separately. Try to keep the pins at right angles to the LCD's PCB to ensure that they will fit squarely into the header sockets on the main PCB.

Mount the bezel to the outside of the lid with the four 15mm-long M3 machine screws, keeping the matte surface facing out. Secure on the inside with four nuts. While simplifying assembly, these nuts also provide the



Tactile switches with long actuators can be hard to come by, although you can certainly use such a part if you can find it. Our assembly uses four wires to stand S1 off the PCB so that you can access it from outside the case.

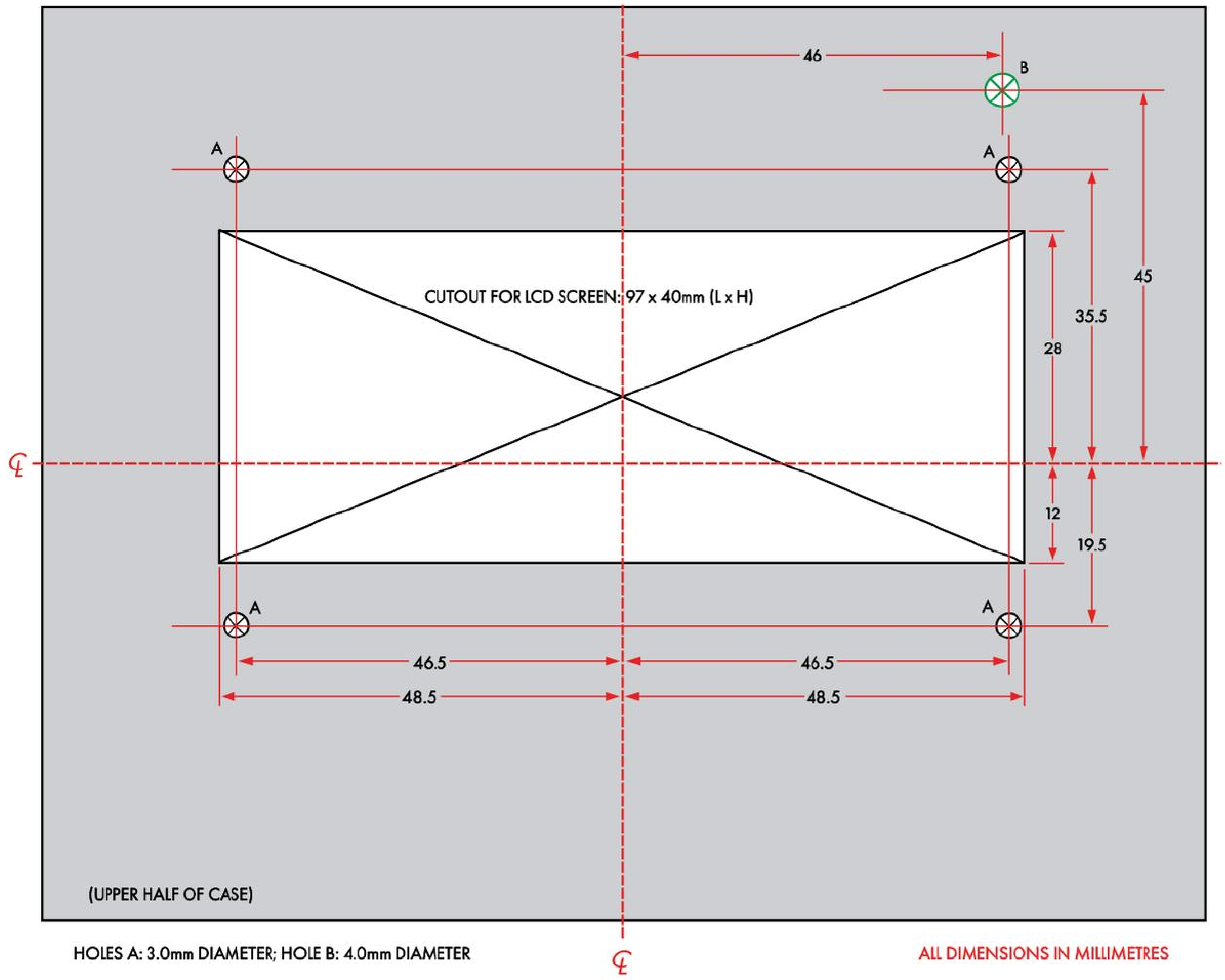

46
B
A
A
CUTOUT FOR LCD SCREEN: 97 x 40mm (L x H)
45
35.5
28
℄
12
19.5
A
A
46.5
46.5
48.5
48.5
(UPPER HALF OF CASE)
HOLES A: 3.0mm DIAMETER; HOLE B: 4.0mm DIAMETER
℄
ALL DIMENSIONS IN MILLIMETRES

Fig.4: fortunately, the laser-cut bezel hides any small inaccuracies in the large rectangular cutout in the case. The LCD mounting holes must be drilled accurately to ensure that the LCD aligns with the PCB underneath. The hole marked in green is used for accessing S1, and is optional.

Scrolling text can be hard to read at some LCD contrast settings, so the revised firmware (C/D) halves the scroll speed and provides a hidden option 4 under calibration to adjust it (1 = original speed, 2 = default, 4 = extra slow).

spacing necessary to clear the top of the headers on the LCD panel.

Slide the LCD module over the machine screws and secure it with the remaining M3 nuts. The top of the LCD panel should sit just proud of the bezel on the outside of the lid. You can see this in our photos at the end of the article.

Using four self-tapping screws, secure the main PCB to the other half of the case. This will allow us to align the headers to the LCD and solder them in exactly the right place. There should be a 20mm gap between the main and LCD PCBs when the case pieces are assembled.

Note that the enclosure will only fit together one way, so check that it slots together with the LCD1 pads on the PCB in line with the LCD panel's pins. If the LCD panel's pins are above the USB sockets when the case is assembled, remove the PCB and rotate it by 180°.

If you have 20mm spacers, you might like to use them (and the three mounting holes on the PCB) to align the LCD. Doing it that way is less fiddly.

Before proceeding, check our photos of how the header sockets are fitted to the main PCB. Note that they only occupy the six end positions of each end of the header; the four central positions are not connected (as they are not used in the LCD's four-bit mode).

Separate the case pieces and slot the sockets onto the LCD's pins as described above. Then place the two case pieces back together. This should align the socket pins into the pads on the main PCB. If you are having trouble, try aligning one edge of the case and pivoting the other end closed. This will bring the pins into location one at a time.

With the pins located, screw the case halves together to secure everything in place. Then use your soldering iron to tack one pin to the main PCB at each end of the two headers (four pins in total) through the side opening. This is easiest at the end near the top of the PCB. Once you are happy they are secure and still correctly aligned, disassemble the case.

Now solder the remaining pins without disturbing the alignment and then refresh any pins that might need it. At this stage, you should be able to reassemble the two halves with the pins lining up and seating into the header, pivoting the case as described earlier.

If you're having trouble with the alignment, you could instead join the LCD to the main PCB with ribbon cable, strands of hookup wire or similar. Keep in mind to follow the correct pin ordering and use at least 5cm of cable for each connection to allow for flex when the case halves are separated.

Remove the main PCB from the case to continue the construction. To simplify testing, we recommend detaching the LCD from the lid to allow the bare PCB to be attached to the LCD and powered up later while allowing access to the test points and jumpers on the PCB.

Soldering the USB sockets

Some of these are surface-mounted, so the usual collection of SMD tools is required. With CON4 and CON6 being some of the finest pitch parts we have worked on, a magnifier is a necessity, as is a good source of bright light. A mobile phone camera set to a high digital zoom level is an excellent alternative to a magnifier.

You should also have a fine-tipped adjustable soldering iron, flux (preferably paste) and tweezers. Fortunately, most of the USB sockets (except for CON8) have locating pins, making exact positioning easy.

Your flux should recommend a solvent to use for cleanup. Some desoldering braid (solder wicking braid) is a cheap and handy thing to have on hand for fixing any bridges or other situations where there is too much solder.

Remember that flux can generate smoke. Use a fume extraction fan or work outside if necessary. Working outside is another way of getting decent illumination.

Start with the mini-USB socket, CON5. Apply flux to the pads, rest the part in place (locking its plastic pins into the PCB holes) and apply a bit more flux to the top of the pins. Ensure that it is flat against the PCB. Also try to keep the part square and

USB CABLE TESTER
Ready for cable.
Battery: 4.7V
SILICON CHIP
Automatic USB Cable Tester
USB-A
USB-C
Downstream Facing Ports
USB-B
USB-C
Micro-B
Mini-B
Upstream Facing Ports

Using the finished USB Cable Tester is as easy as plugging one end of a cable into a Downstream Facing Port, the other end into an Upstream Facing Port and then checking the LCD for its assessment.

parallel to the PCB so it will align correctly with the front panel.

Clean the iron's tip and apply some fresh solder to it. Then apply it to the point where the pins meet the pads. If you can't get in close, try applying the iron to the extended pads and allow them to draw solder off the iron tip.

If you get a good fillet at the point where the pin meets the pad, then all is well. Do the remaining pins, then turn up the iron slightly to secure the mechanical pads. Clean the tip and add fresh solder as needed.

Pay attention to the mechanical pads, as these sockets will see a rough life and be subjected to repeated insertions and removals. There is also a through-hole pad accessible from the reverse of the PCB to help secure the shell of this part.

Flip the PCB over and apply the iron to the pad. Gently feed in solder until the hole fills up. There should already be flux present if you have used it generously; if not, add a little more.

Now use the same technique for CON8, the micro-USB socket. It has no locating pins, so you will have to take extra care with its alignment. Its front should be parallel with CON5 and its pins centred in their pads. Work one pin at a time to avoid bridges. If you get a bridge, remove it with extra flux and solder braid.

Like CON5, turn up the iron to solder the larger mechanical pads. There are also extra pads underneath the PCB to help secure CON8; solder these similarly.

CON4 and CON6 are the trickiest part of this build; the other two remaining USB sockets (CON3 and CON7) are through-hole only parts. The most significant trouble we had with pins on these parts bridging was when solder crept up to where they sit closer together, near their tops.

If you keep your iron down near the PCB and just on the PCB pads only, you should avoid that problem. Apply flux paste before placing the socket, then add more before soldering the pins.

Set up your magnifier to give you a good view, clean the iron tip and apply fresh solder. You'll see that two of the 12 pins have shorter PCB pads; these are not connected in circuit, so they do not have to be soldered.

Solder the surface-mount pins, adding flux, cleaning the iron tip and adding solder to it as needed. Inspect your work closely, as it's only possible to easily remove the part and start afresh if the other through-hole pins haven't been soldered.

If you think there might be bridges, use more flux and solder wicking braid to remove them. Take care not to allow solder onto the upper parts of the leads.

Remember that flux can make inspecting solder joins difficult. You can avoid the hassle of cleaning the entire board of flux for inspection by gently wiping away the flux with a cotton bud dipped in an appropriate flux solvent.

When you're happy with the top of the PCB, flip it over and solder the through-hole pins. These are closely spaced too, but surface tension should keep the solder where it needs to be, and you can also use solder braid to remove bridges here.

Turn up the iron and solder the four mechanical mounting pins. For these, more solder is definitely better than less. Add some solder to the two central pads under the connector to help with mechanical strength.

It might look like two pairs of the through-hole pins on each of CON4 and CON6 are bridged; the two outermost pairs in the row of eight. This is fine as they are all connected to their respective socket's GND pin. You can check this against the circuit diagram and overlay.

We suggest leaving CON3 and CON7 until you can complete the self-tests, which will involve getting most of the *USB Cable Tester* functional.

You can fit inductor L1 and the 220mΩ resistor now. Neither is polarised, so apply flux, rest the part in place and tack one lead with the iron. You may need more heat on L1 due to its size. Solder the second lead on each part, then go back and refresh the first lead if necessary.

Now is a good time to clean up any flux that may be present on the PCB, given that all the surface-mounting parts have been fitted and there will be little need for more flux paste to be used. This will allow closer inspection of your soldering.

Your flux should recommend a cleaning agent, but isopropanol or methylated spirits are good alternatives. Ensure that the board is allowed to dry and that any flammable solvents have a chance to evaporate before you get back to soldering.

Use your magnifier to examine the cleaned PCB. Any faults you can pick up now will be easier to see and repair before more components are fitted and may be more apparent now that the flux has been cleaned up.

If you're unsure about your soldering, use a multimeter to check for continuity between the bottom ends of where the 26 1kΩ resistors will be fitted in the middle of the PCB, since these all go back to the USB sockets. If you find any short circuits, you can use the circuit diagram and overlay to identify the affected connector and pins.

Through-hole parts

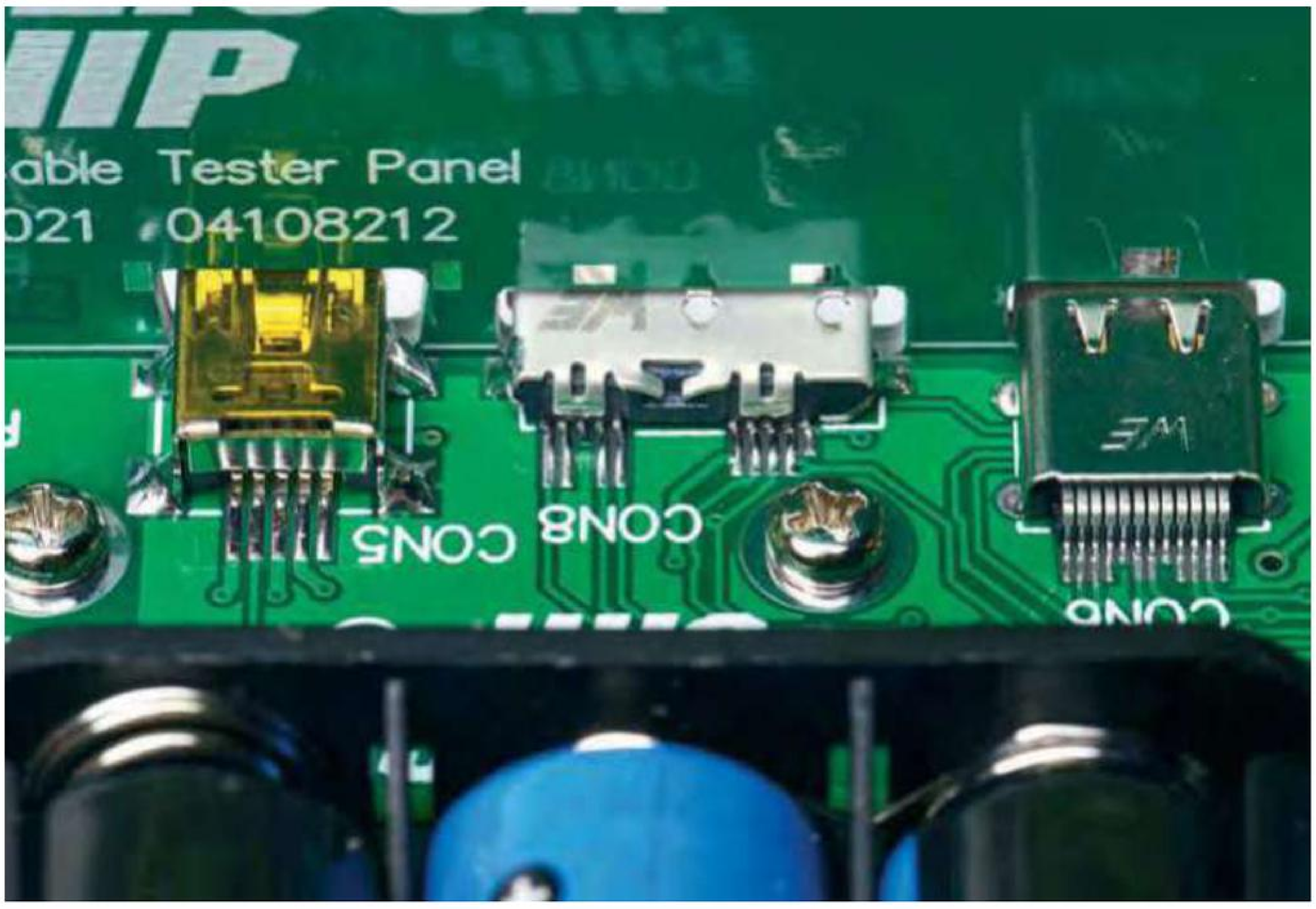
Continue by fitting the resistors, referring to the overlay diagram (Fig.3) as a guide. Fit the four 10kΩ parts first, then the 28 1kΩ resistors, then the rest. Check the resistances with a multimeter if you are not confident of the part markings. The 100Ω, 1kΩ and 10kΩ resistors only differ in one colour band. Once identified, solder them in and trim the leads close.

To get the LCD operating so we can run the tests, we need to fit all the parts above and including IC1, except S1 and S2. If you don't have a pre-programmed microcontroller, you should install CON2 to permit programming in-circuit.

Now fit D2, the 100nF capacitor near IC1, 10kΩ trimpot VR1, Q1 and CON2 if needed (we recommend a vertical header for CON2).

Be sure to align Q1 and VR1 to the silkscreen pattern. Also solder the battery holder to CON1, running red to '+' and black to '–'.

Check that D2 is a 1N5819 and that its cathode stripe faces as shown on the silkscreen. You don't need a header



A close-up view of the soldered pins on some of the USB sockets. This is what you want the solder joints to look like; glossy, with clear fillets between the PCB pads and socket pins, and no bridges between them. Elongated pads are provided for many of the pins which make soldering them significantly easier.

at CON1; you can solder the wires to the pads. The holes near CON1 are for strain relief, so thread the battery leads from below the PCB into the tops of the holes and then solder from below (see photos).

While there is room to fit a socket for IC1, we don't recommend you use one. For a start, the large number of pins will make fitting and removing IC1 tricky. We only used one to allow us to test different microcontrollers.

Gently bend IC1's pins to slot into the PCB, making sure that the pin 1 marker goes to the left as shown. Tack down two pins on opposite corners and check that the part is flat and oriented correctly. Adjust if needed and then solder the remaining pins of IC1.

Before we move on to the start of the testing, we first need to program the chip.

Programming

Install cells in the battery holder to power the circuit (unless you have a programmer that can supply up to 25mA at 4.5-5V). You can use a PICkit 3, PICkit 4 or Snap programmer.

We use the MPLAB X IPE for programming; it can be downloaded (along with the MPLAB X IDE) from **www.microchip.com** under the 'Tools and Software' tab.

Select the PIC16F18877, click 'Apply', select your programming tool and click 'Connect'. Open the HEX file **0410821C.HEX** using the 'Browse' button and then press 'Program'.

If you see a 'Program and Verify successful' message, all is well. Otherwise, check the wiring and soldering around the five tracks that go to CON2 from IC1.

Two of the programming pins (PGD and PGC) are also used for probing the USB sockets at CON3 and CON4, so make sure that they are not shorting to anything else.

If you have opted to use a PIC16F18875, use the **0410821D.HEX** file instead (Both of the Hex files are available from last month's download bundle on the November 2022 page of the the *PE* website.) Our original prototype used a PIC16F18875, which is why the PCB is marked with this part number.

We decided to standardise on the PIC16F18877 as we think it will be more useful in the future and doesn't cost much more (it has more room for expansion). Though they are from the same family, some of their special function registers are in different locations, so remember that the HEX files are *not* interchangeable.

When finished, detach the programmer and power down the circuit (eg, by removing the cells).

Testing

Plug the LCD into its headers, apply power and adjust VR1, the LCD contrast control, until the display is legible. You should see a splash screen with a countdown timer, followed by the main *USB Cable Tester* screen.

You can check the contrast voltage at VR1's wiper. Our unit reads around 1V with a fresh battery.

If you see a 'Ready for cable.' message after seven seconds, construction is correct so far, and your USB socket soldering has no detectable faults. The Battery value should be between 4.2V and 4.8V. You can compare this with a multimeter voltage reading between TP1 and TP2; if the reading here is roughly correct but the displayed value is not, the circuit has a problem.

If all is in order, then you can progress to the remainder of the construction below.

Problem?

If there is no LCD backlight, there's likely a problem around transistor Q1. If you can light the backlight by grounding the LED cathode (pin 16) of the LCD, then it's definitely the PCB components and not the LCD.

If you get a message on the LCD listing the UFP or DFP, these messages will point to USB socket pins that might be shorted. Refer to the circuit diagram and overlay to find those pins. Disconnect the power supply, check and make repairs, and then test again until you get the 'Ready for cable.' message.

Remaining components

Fit the three remaining capacitors. The two 1000µF and one 10µF electrolytic capacitors all have their positive (longer) leads facing to the right, according to the PCB silkscreen.

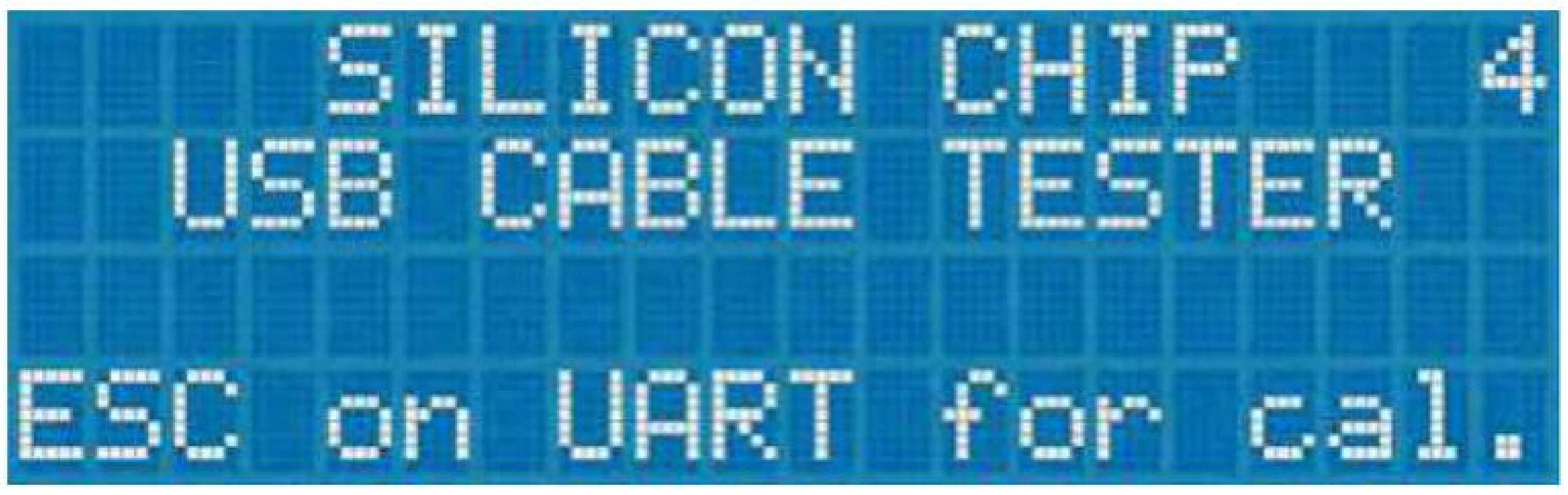
Slot the two remaining USB sockets (CON3 and CON7) into place. Tack a couple of leads and ensure that the parts are flat against the PCB and squarely aligned to the PCB. This will help align the sockets to the front panel.

When the sockets look correct, solder the remaining pins and be generous with the mechanical tabs to ensure that they have the necessary mechanical strength.

There are two more diodes. Fit the single 1N4148 near CON4; it will sit between the two relays and is easier to fit before them. Check that its cathode stripe aligns with the silkscreen markings. The remaining diode is D3, a 1N5819 near L1.

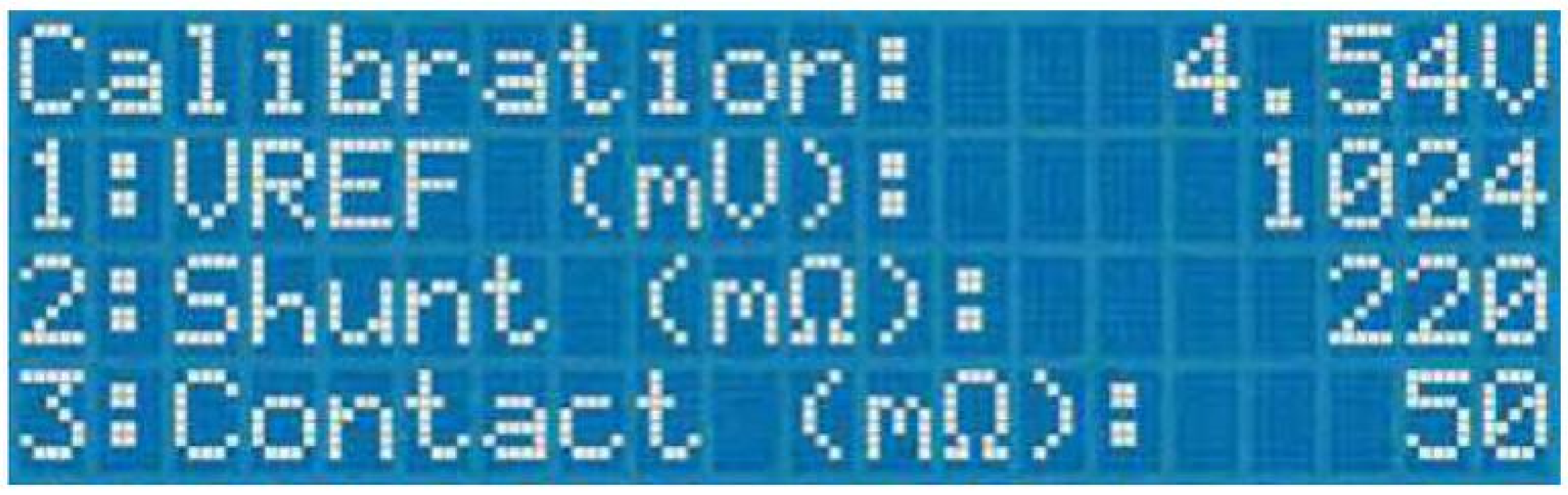
Then fit the two relays, RLY1 and RLY2. They should have one end marked with a stripe that will match the line on the PCB at the end nearest to IC1. As for any multi-lead part, solder a couple of pins and check that the device is correctly positioned before soldering the remaining pins.

Then fit the other 2N7000 MOSFET (Q2) near RLY2 and Q3 – the larger TO-220 P-channel MOSFET, near L1. Its marked face should be towards L1 with the tab closest to the cutout in the PCB. Ensure Q3's leads are pushed down against the board so that it doesn't foul the enclosure lid.



```
   SILICON CHIP    4
  USB CABLE TESTER

ESC on UART for cal.
```

Screen 1: on reset, the calibration prompt is displayed. This splash screen is shown for seven seconds. Calibration mode is entered if the USB Cable Tester receives an ESC character via the CON9 serial header during that time.



```
Calibration:   4.54V
1:VREF (mV):    1024
2:Shunt (mΩ):    220
3:Contact (mΩ):   50
```

Screen 2: the Calibration screen has four options which are accessed by sending a 1, 2, 3 or 4 character. Sending Ctrl-C at any time will exit calibration mode. The measured battery voltage is displayed at top right to assist calibration.

Options

The remaining parts are optional and only really needed for calibration (which isn't required). However, as we noted in the last month's article, you can also use S1 to wake up the *USB Cable Tester* without plugging in a cable. This could be handy if you are often testing just one end of a cable.

The UART header (CON9) is only needed to enter calibration mode via a USB-serial module. S2 can be used to reset the microcontroller and quickly jump in and out of calibration mode.

JP1 and JP2 are used to calibrate out the resistance of the internal wiring and traces.

The other two calibrations are for the microcontroller's internal 1.024V reference voltage and current-sense shunt resistance. The internal reference is specified to be accurate within ±4%, so the *USB Cable Tester* will be perfectly functional without calibration, but it will be slightly more accurate if this is done.

The current sense resistor should be within 1% and won't need adjustment. The measured voltage is around 100mV with 1mV resolution, so the shunt resistance only needs to be adjusted if you can't use the specified shunt value.

Values from 100mΩ to 500mΩ should work, although we have only tested the specified 220mΩ value. Lower values will give less accuracy, while higher values reduce the headroom to measure voltage drop in cables.

Fit CON9 with the pins facing up; this will allow a pair of jumper wires or similar to be connected between the USB-serial converter and the PCB.

Fit the JP1 and JP2 headers but leave the jumper shunts off for now, or plug them onto just one pin of the header.

S2 fits flat against the PCB as it is only used for setup and calibration. It shouldn't be accessible during normal use. Snap it into the pads and ensure it is flat against the PCB before soldering.

If you want to make S1 available for use after calibration, you need to drill the extra hole shown in Fig.4 and mount S1 above the PCB, near the top panel.

To align everything, attach the main PCB to the enclosure using one screw in each corner. Use lengths of tinned copper wire to attach S1 to the PCB. Align S1 to the inside top of the front panel with some tape or Blu-Tack, then, after placing the lid on top, tack solder one of the wires in place.

This just needs to be enough to locate S1. Remove the tape and the lid. With the better access this provides, add more wires to secure the switch on all four corners.

If you don't need external access for S1, it can be simply soldered flat against the PCB like S2.

This completes the soldering for the *USB Cable Tester*. Double-check your work, then plug the LCD into its header.

Calibration

If you wish to perform calibration, connect a USB-serial converter to CON9 using female-female jumper wires. If you are using a CP2102 type (like us), the pin marked 'TXD' on the converter connects to R on the PCB. GND on the converter connects to '–' on the PCB.

Only one data line needs to be connected as the *USB Cable Tester* displays its prompts and responses on the LCD instead of the serial terminal.

Open a serial terminal program (eg, TeraTerm) and connect to the USB-serial converter at 9600 baud, 8 bits, no parity, one stop bit (8N1). It won't matter if your USB-serial converter has 3.3V or 5V signals. The 1kΩ resistor will limit the current flow, and IC1 will recognise logic levels in this range.

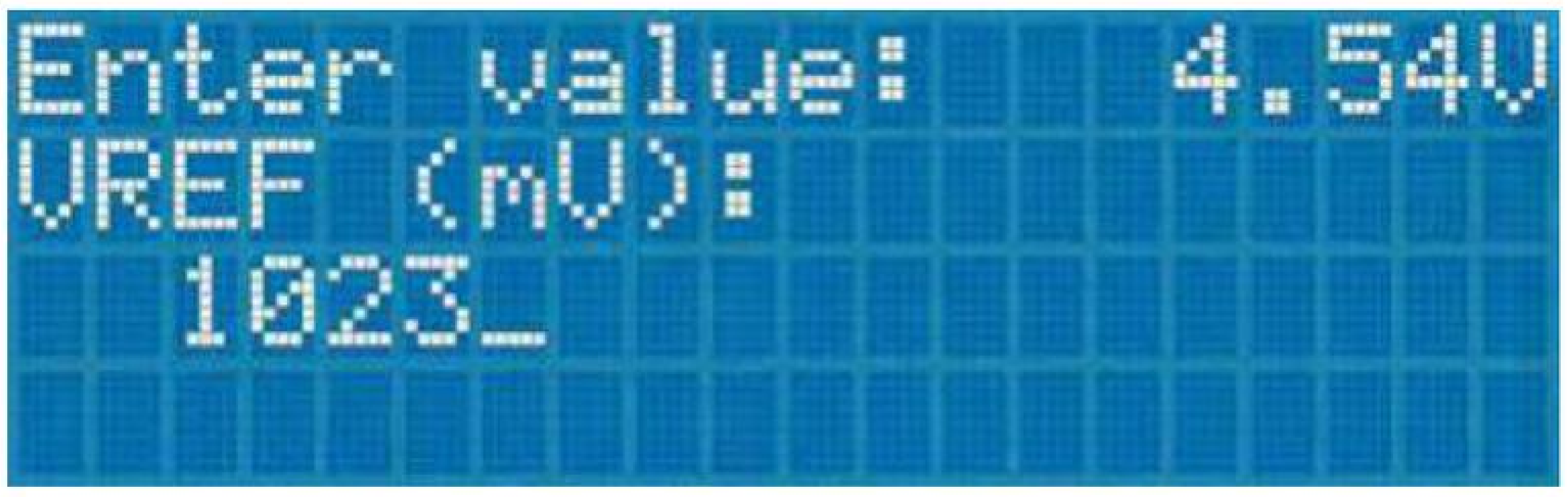
Now power up the *USB Cable Tester* PCB. When the prompt shown in Screen 1 is visible, press the ESC key on the serial terminal. If communication is working correctly, you should see Screen 2. If not, check your wiring and reset the micro with S2 to get the prompt to press ESC again.

At Screen 2, you can press 1, 2, 3 or 4 on the terminal to change the displayed value, as seen in Screen 3, after which you are prompted to confirm the change (Screen 4) with 'Y' or 'N'. If you press 'Y', you will see something like Screen 5.

To calibrate the VREF value, measure the supply voltage between TP1 and TP2 and compare this with the displayed voltage shown at top right. The internal voltage reference is in *inverse* proportion to the displayed voltage.

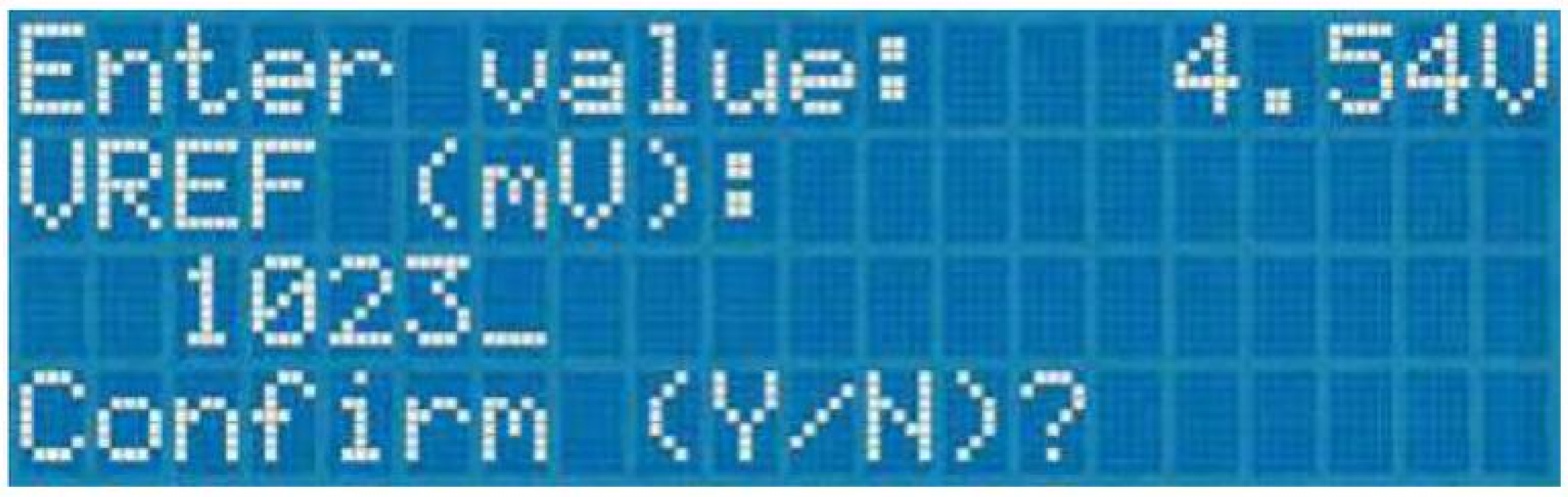
So if the displayed voltage is 1% too high (for example), increase the VREF value by 1% of its current value. With the internal reference specified being accurate to within 4%, you should not need to change this up or down by more than 40 points.

Another way to calculate this is that an error of 0.01 in the displayed voltage (ie 10mV) is equivalent to about 2.1 VREF steps. So if the displayed value is 4.68V instead of 4.65V, add 6 points to the VREF value.



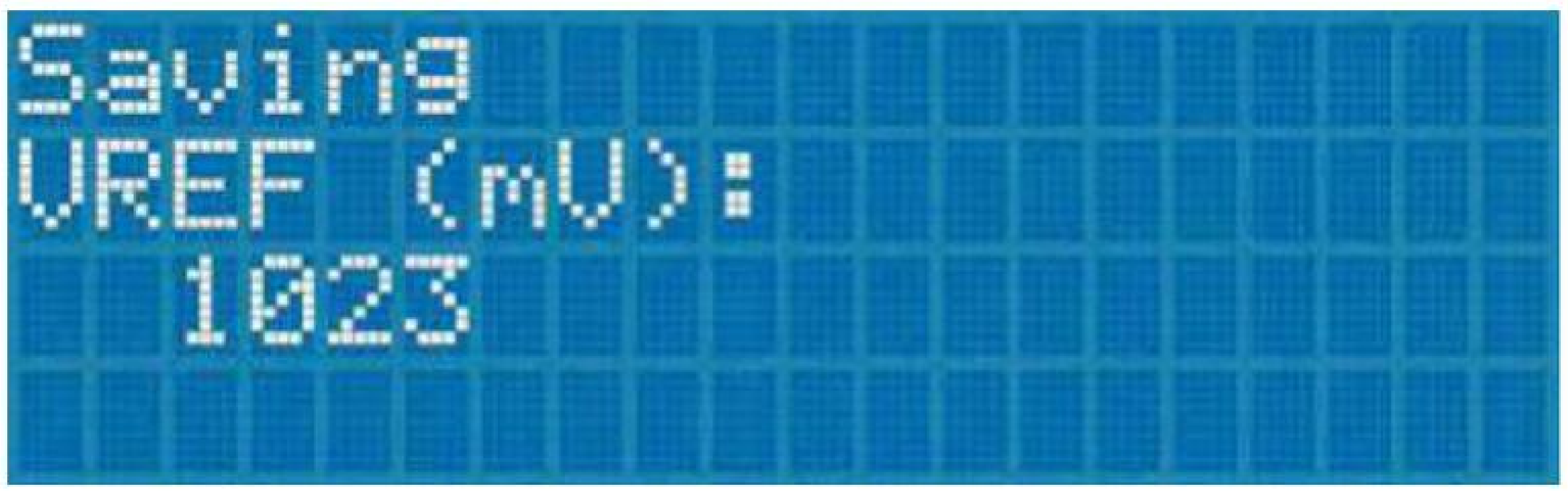
```
Enter value:   4.54V
VREF (mV):
  1023_

```

Screen 3: each calibration value is entered in decimal. The value can be accepted by pressing Enter (CR, ASCII code 13) or cancelled by pressing ESC. You can clear the last keypress with delete or backspace.



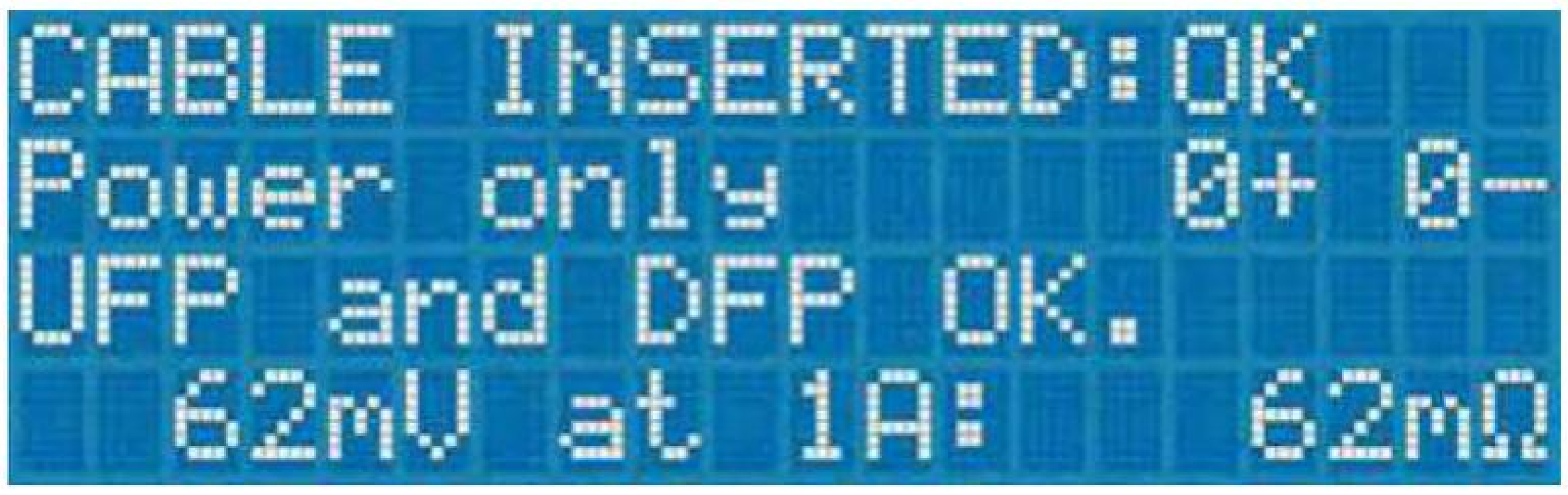
```
Enter value:   4.54V
VREF (mV):
  1023_
Confirm (Y/N)?
```

Screen 4: there is a final confirmation prompt before an entered value is committed to EEPROM. To answer the prompt, enter either upper or lower case 'Y' or 'N'.



```
Saving
VREF (mV):
  1023
```

Screen 5: while the value is being saved to EEPROM, it is also displayed as a final check before returning to the main Calibration screen.



```
CABLE INSERTED:OK
Power only    0+ 0-
UFP and DFP OK.
  62mV at 1A:   62mΩ
```

Screen 6: with JP1 and JP2 fitted, only the Tester's internal resistance is reported. The value at the bottom of the screen is the contact resistance value. A similar screen is seen when a power-only cable is plugged in for testing.

The nominal shunt value should be accurate enough. You can measure the shunt resistance any time the relays are inactive (all the time in calibration mode) and there are no cables plugged in. Measure between TP1 and TP3.

To calibrate the relay contact resistance, use option 3 to set this to 0mΩ. Then exit calibration mode by pressing Ctrl-C on the terminal or resetting the microcontroller.

Attach jumper shunts to JP1 and JP2. This will simulate a power-only cable being connected, and you should get a display like Screen 6. Note down the resistance value shown, then remove the shunts.

Reset the micro again and go back to calibration mode with ESC on the terminal. Save the noted value as the contact resistance and exit calibration. If you reattach JP1 and JP2, you should see a value very close to zero.

At this stage, you can try out the *USB Cable Tester* on any USB cables you have lying around. See the *Usage* section for further information.

Final assembly

Power down the unit by removing the cells, detach the LCD from its header and reattach it to the lid as described earlier.

Put the front panel PCB over the USB sockets on the main PCB and slot the pair of PCBs into place in the base of the enclosure. Secure the main PCB to the enclosure using the eight self-tapping screws.

There are solder pads on the inside of the front panel PCB, so the panel can be affixed to the main PCB by soldering these pads to the USB sockets.

The battery holder may have screw holes, but to avoid marring the underside of the enclosure, we suggest gluing it with neutral-cure silicone or construction adhesive. If you do use screws, fit self-adhesive rubber feet to the underside of the box to prevent the screws from scratching any surfaces.

Slot the rear panel supplied with the case in place, then fit the cells. Carefully position the enclosure lid, feeling that the LCD header locks in place. The LCD backlight may illuminate if the unit has not gone to sleep, but there won't be a meaningful display since the LCD controller will not have been properly initialised.

Allow the unit to go to sleep (the LCD backlight will go off), then plug in a cable (or press S1) to wake it up; this should reinitialise the LCD, and you should see one of the cable reporting screens (or the idle screen). If this is the case, all is well, and you can secure the two halves of the case with its two included screws.

Usage

Screens 7-11 show the *Tester* in use. Screen 7 is the idle screen, which shows the battery condition and time until the unit enters low-power sleep mode. It is present when the unit is awake, but no cable is detected.

Once a cable is inserted, you should see the full diagnostic display, as seen in Screen 8. The first line shows a broad pass/fail assessment of the cable.

The second line identifies the USB rating and the number of short circuits (+) and open wires (–) detected. For an OK result, these are both zero. The third line shows more detailed information depending on the test results, listing the wires involved in any short or open circuits detected. The text may scroll if it doesn't fit on one line.

As shown in Screen 11, the results of the UFP and DFP tests are summarised so that single-ended tests may be carried out. This is done by unplugging one end of the cable at a time, leaving just the UFP or DFP connected.

It's common that the DFP and UFP tests will detect that GND is shorted to the shield. This is the case for some USB-C cables and doesn't seem to cause any problems.

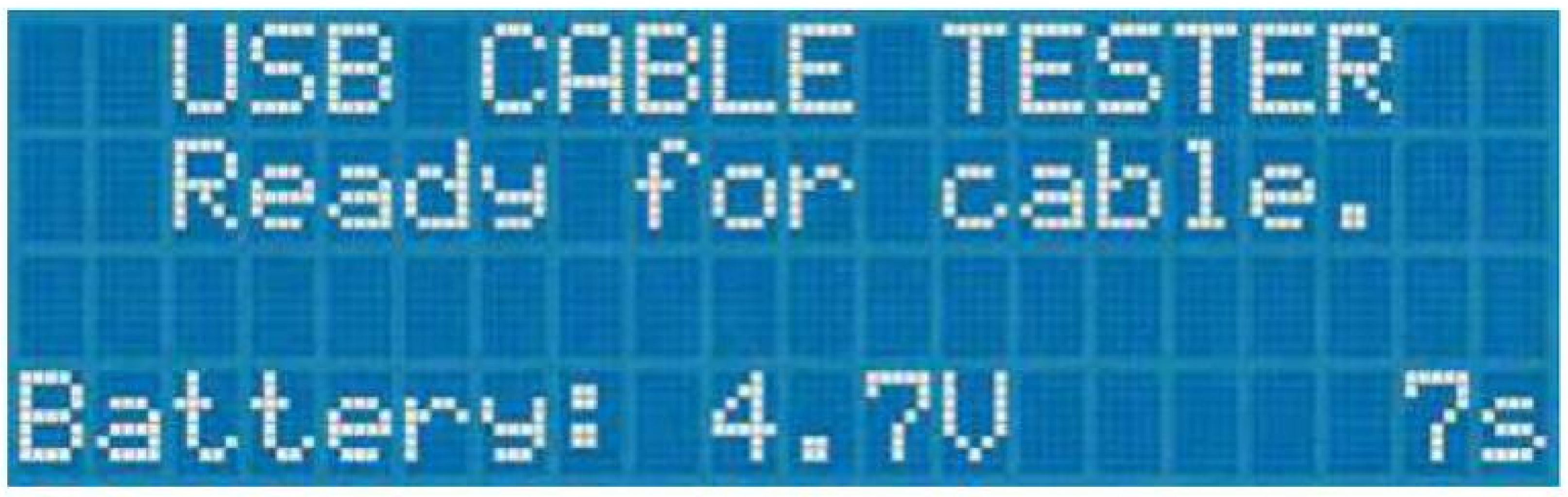
The final line summarises the results of the current pulse test. Values around 200mΩ can be expected for cables in good condition. Up to around 500mΩ, they could work fine, especially for light loads; higher values indicate a cable that may cause problems.

You can test cable combinations, such as when a cable is supplemented by a USB extension cable. However, as we noted, high-speed signal integrity is not tested by the *USB Cable Tester*.

If you want to check a USB extension cable, first test a cable with a plug that will fit into it on one end (ie, A-type or C-type) and a B-type or C-type on the other; ideally, a USB 3.2 SuperSpeed type, although you can still do the test if you don't have one.

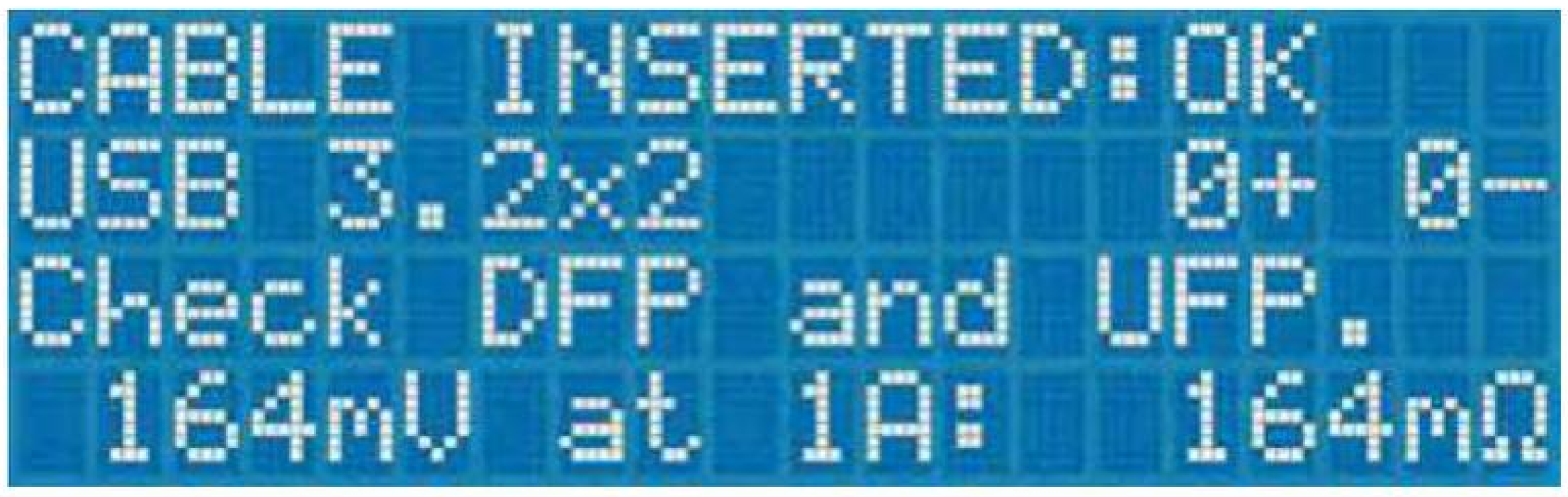
Verify that cable is good and note its type and resistance. Then plug that cable into the extension cable and test the combination. Subtract the resistance reading noted earlier from the new reading to measure the extension cable's own resistance

Screen 9 shows what might be seen if the cable has a fault; the first line indicates this. The second line lists the nearest 'working' cable type to what has been detected and also the number of faults present; in this case, '1–' means that this is most likely a USB 2.0 cable but with one conductor open circuit.



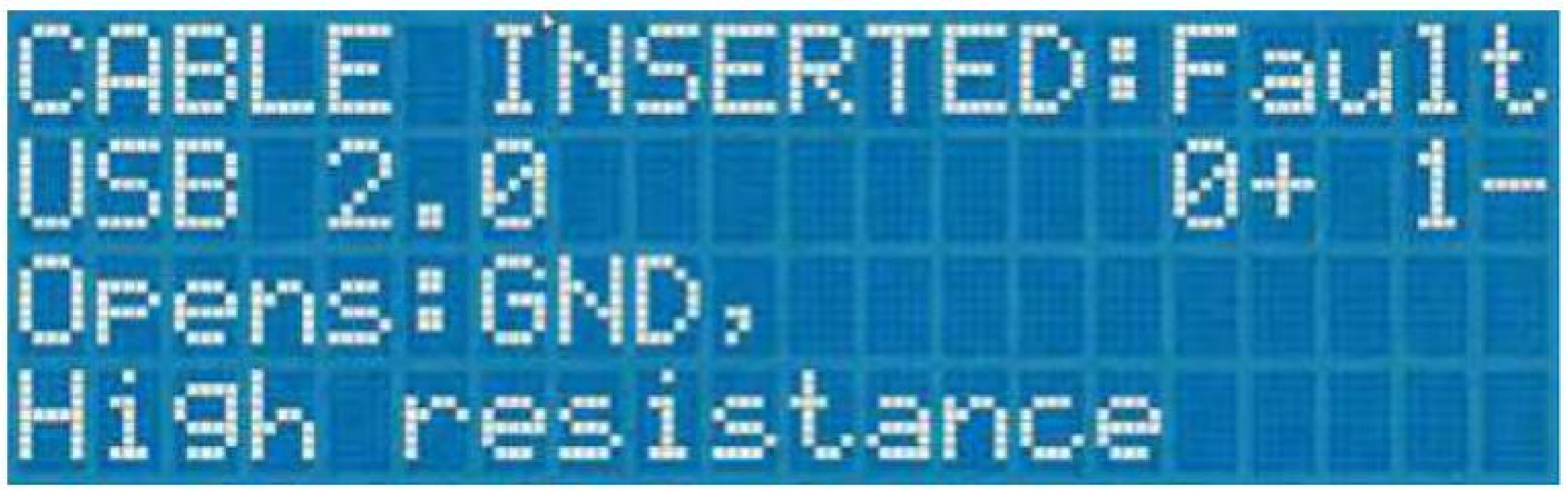
```
  USB CABLE TESTER
  Ready for cable.

Battery: 4.7V       7s
```

Screen 7: once calibration is complete, the main idle screen is shown unless a cable is plugged into the ports. The battery condition is reported and the sleep timer counts down 10 seconds before entering low-power sleep mode.



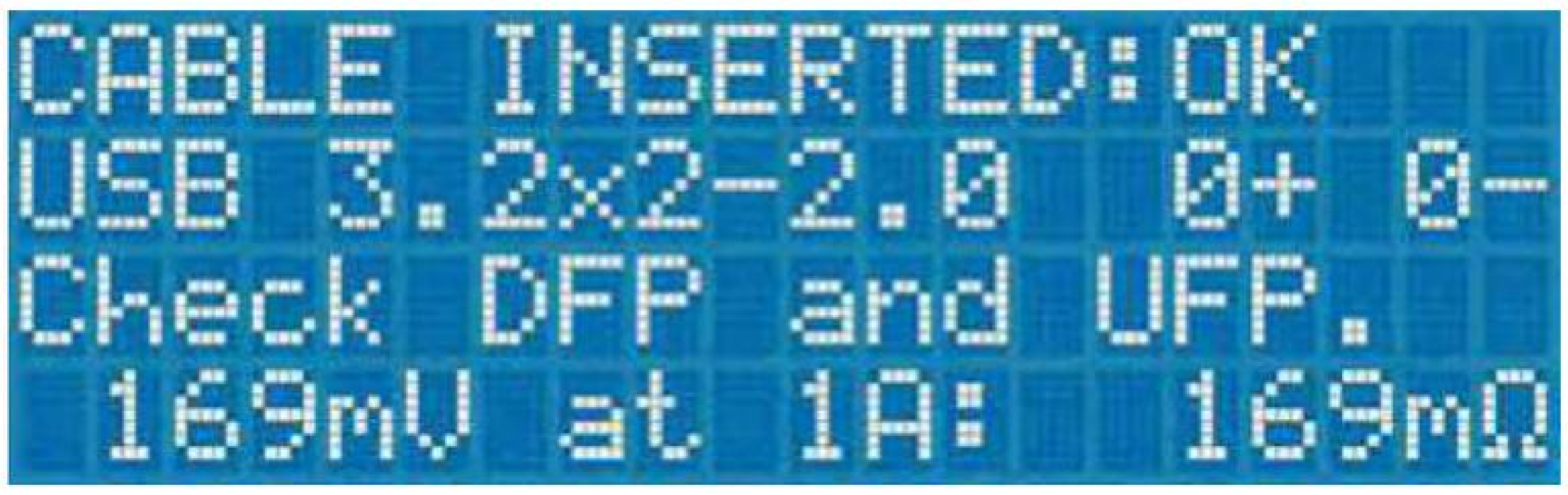
```
CABLE INSERTED:OK
USB 3.2x2      0+ 0-
Check DFP and UFP.
 164mV at 1A:  164mΩ
```

Screen 8: a typical test result on a USB-C to USB-C cable shows what is expected for a fully USB 3.2 compatible cable with two SuperSpeed lanes, meaning that it has the USB 2.0 D+/D– pair as well as the SuperSpeed wires.



```
CABLE INSERTED:Fault
USB 2.0        0+ 1-
Opens:GND,
High resistance
```

Screen 9: the Cable Tester will elicit a variety of information about a faulty cable, including what it thinks it ought to be and what problems it might have. Here, an open GND wire means that the cable will not function, even for charging.



```
CABLE INSERTED:OK
USB 3.2x2-2.0  0+ 0-
Check DFP and UFP.
 169mV at 1A:  169mΩ
```

Screen 10: with USB-C cables being reversible, it's necessary to test them with both insertion orientations. If this screen is seen, the current orientation does not connect the D+/D– pair and you should try another orientation.

The third line indicates that the open wire is the GND conductor, so it is unlikely to work at all. The 'High resistance' message is only shown when the cable is incapable of carrying the lowest 100mA test current.

The display in Screen 10 needs some explanation. USB-C leads only have one D+/D– pair (the wires required for a legacy USB 2.0 connection) but can be plugged in one of two ways, and some cable orientations do not detect this pair.

In this case, the USB 3.2x2-2.0 indication is shown. That means that two of the SuperSpeed lanes needed for a USB 3.2 connection are detected, but the USB 2.0 wires are not. For these cables, you must try each USB-C plug both ways around (rotated 180°).

If only one end is USB-C, run the test one way and flip it to try the other. If you have USB-C at both ends, flip one end, flip the other, then flip the first end back; this will test all four plug orientation combinations.

You should get a USB 3.2x1 or USB3.2x2 result for only one of these tests, with the USB 3.2x1-2.0 or USB 3.2x2-2.0 indication for the remainder. That is, unless your cable has an extra D+/D– pair, which is non-standard, but it could still work on some devices.

If all the combinations show USB 3.2x1-2.0 or USB 3.2x2-2.0, there is a problem with the D+/D– pair either being missing or open circuit. The x1 designation means one SuperSpeed lane is present, while x2 means two lanes, which is only possible with a USB-C to USB-C cable.

Screen 11 shows a typical UFP-only test result. If short circuits are detected in both the UFP and DFP simultaneously, but no continuity is detected between the two ends, then the UFP and DFP screens will alternate. This either means your cable has failed very badly or (more likely) you have two different cables plugged in.

For Screen 11, one end of an OTG cable has been plugged in. The fourth line shows a specific message for this case – it has detected that the GND and ID wires are connected. Only short circuits are shown on this screen, as usually, there should be no connections between pins.

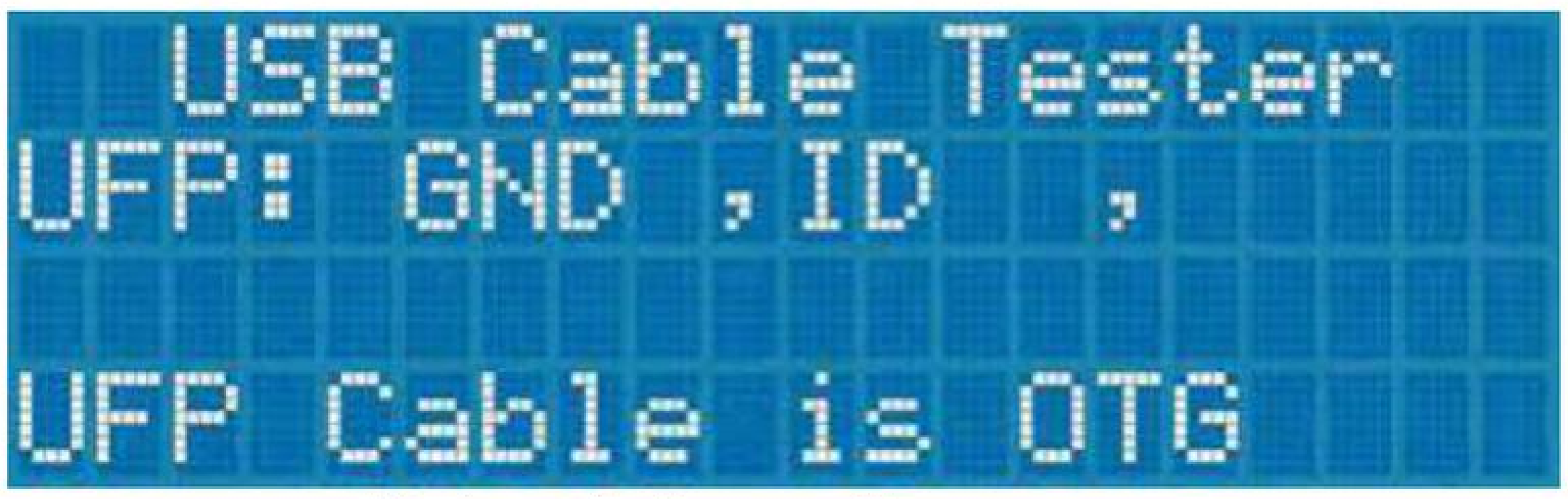
If four or more pins are listed, they might not all be shorted together, but they will all be shorted to at least one other pin. Up to 11 wires can be displayed, so there might be more than those shown if the screen is full.

Also remember that you must always connect a cable between one of the UFPs and one of the DFPs. For example, a normal USB-A to USB-C cable can be plugged into the two DFP sockets, but this will not give a meaningful result; the USB-C end should instead be plugged into the UFP socket.

Conclusion

With this comprehensive and easy-to-use piece of test gear, you can now sort through all your old USB cables and see whether they are worth keeping. With a 30μA sleep current, the *USB Cable Tester* will happily sit for years on the shelf, always ready.

For a final flourish to your *USB Cable Tester*, you can carefully apply some white acrylic (or similar water-based paint) to the etched text on the front of the LCD bezel. Wipe the excess away with a damp cloth and allow to dry.



```
  USB Cable Tester
UFP: GND ,ID   ,

UFP Cable is OTG
```

Screen 11: a typical use for the single-ended cable tests is checking if OTG cables correctly ground the ID pin. Here we see that is that case, with a specific message provided on the bottom line.

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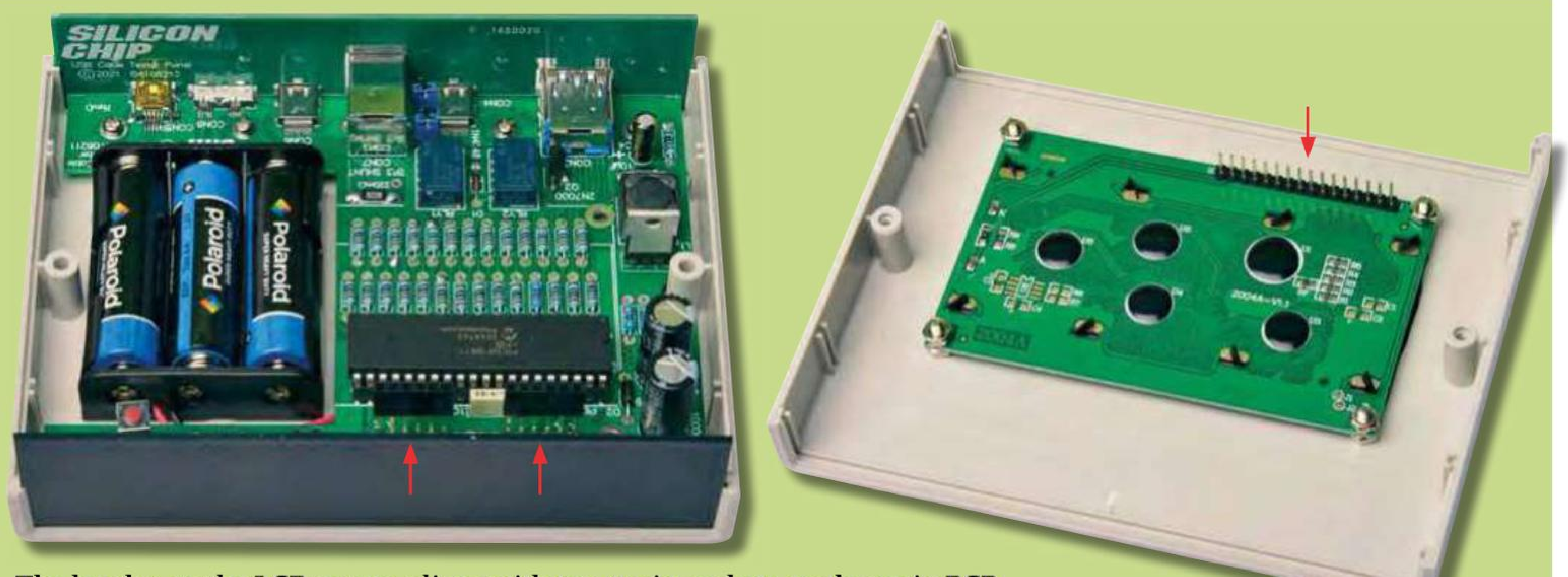
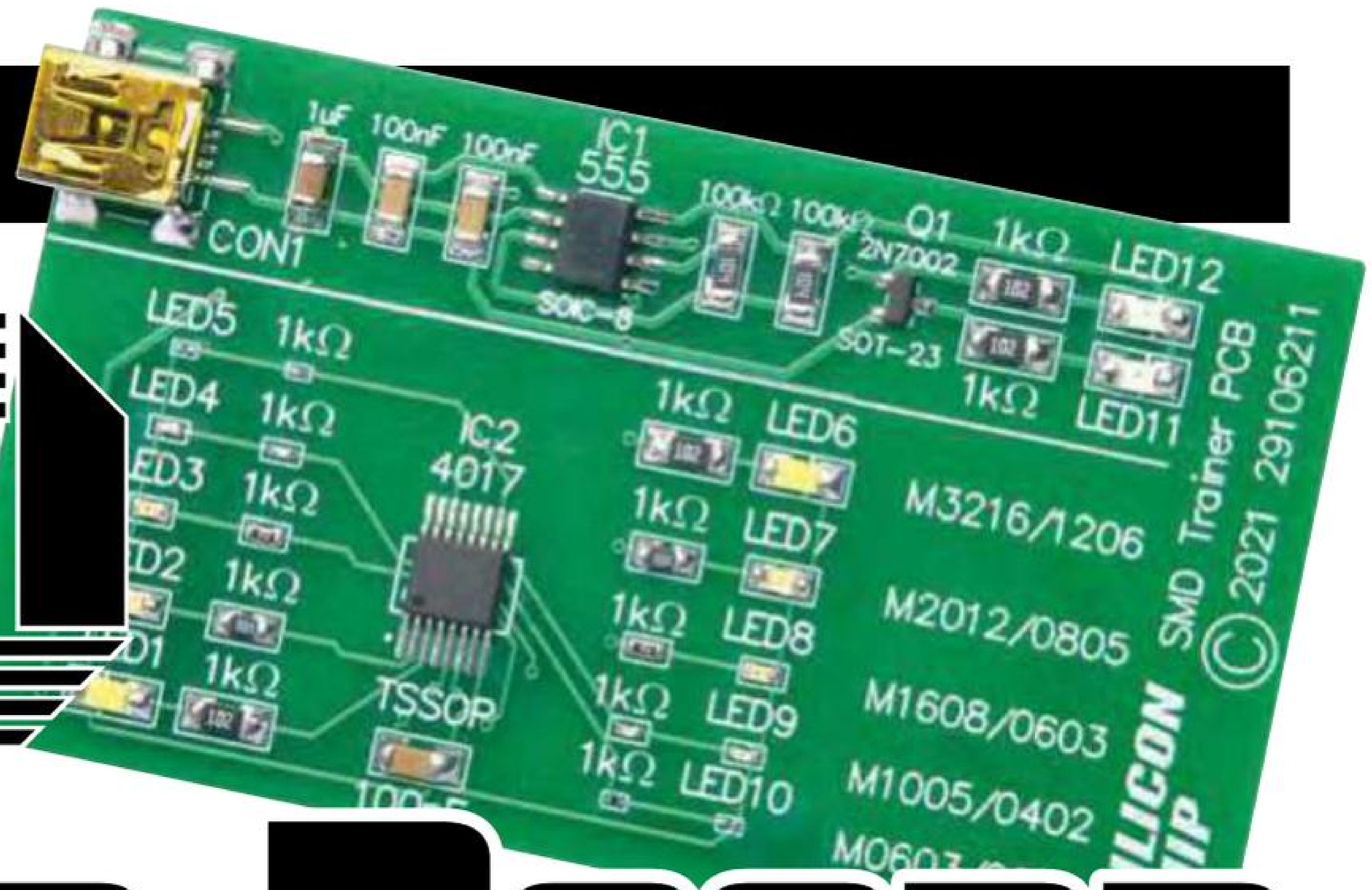


The header on the LCD screen aligns with two 6-pin sockets on the main PCB.

By Tim Blythman



SMD Trainer Board

Are you interested in learning to solder small surface-mount devices but don't want to ruin an expensive board or chip gaining those skills? Perhaps you have no choice but to learn since so many parts made these days only come in SMD packages. This simple SMD Trainer project is a great way to practice soldering a variety of surface-mount devices. If done correctly, you'll be rewarded with a series of LEDs flashing in sequence.

Surface-mount devices (SMDs) are the preferred type of parts used in most commercial equipment due to their compactness, good reliability, low cost and widespread availability. While some manufacturers are still producing new through-hole parts, your choices become a lot more limited if you can't handle SMDs.

We know it seems daunting initially (it did to us, too), but you will be surprised how easily you can do it with a bit of practice. And that's precisely what this board is designed for. It's a working circuit designed using a wide variety of different SMD parts, allowing you to try out soldering them. This way, you can master the techniques and become familiar with the common sizes and packages.

It's designed so you can start with the larger parts and, as you gain confidence, move onto the smaller ones. And you can test it along the way, so you'll find out pretty quickly if you've made a mistake and have an opportunity to correct it.

This article includes the basic instructions for building and testing the *SMD Trainer Board*, along with a description of how it works. The accompanying article provides considerably more detail regarding the necessary tools and techniques.

We recommend that you look at that article now and refer back to it later if you come across anything that you don't fully understand. That's especially the case if you are not experienced at soldering, or have doubts about your ability to handle SMDs.

Assuming you have read that article (at least in part) and are starting to get an idea of how you would go about assembling this board, let's move on to describing its design.

Circuit details

The circuit of the *SMD Trainer Board* is shown in Fig.1. We'll explain how it works before going any further. It's important to know what it should do, so that you can figure out what's wrong if it doesn't work initially.

There are two main parts to the circuit, the second of which depends on the first. The first part of the circuit is also easier to build, so you can try out your skills on that before dialling up the difficulty.

Common to both parts is the power supply. Coin cell holder BAT1 is paralleled with a USB socket, CON1. Only one of these should be fitted. We recommend the coin cell holder, as a coin cell is less likely to deliver damaging current in case you make a mistake building it.

Due to the presence of a coin cell, take care that the *SMD Trainer Board* is kept out of reach of children (swallow/choke hazard). It has flashing lights, so it will appeal to curious eyes – but there is no reason for it to come into a child's hands as it is definitely *not* a toy.

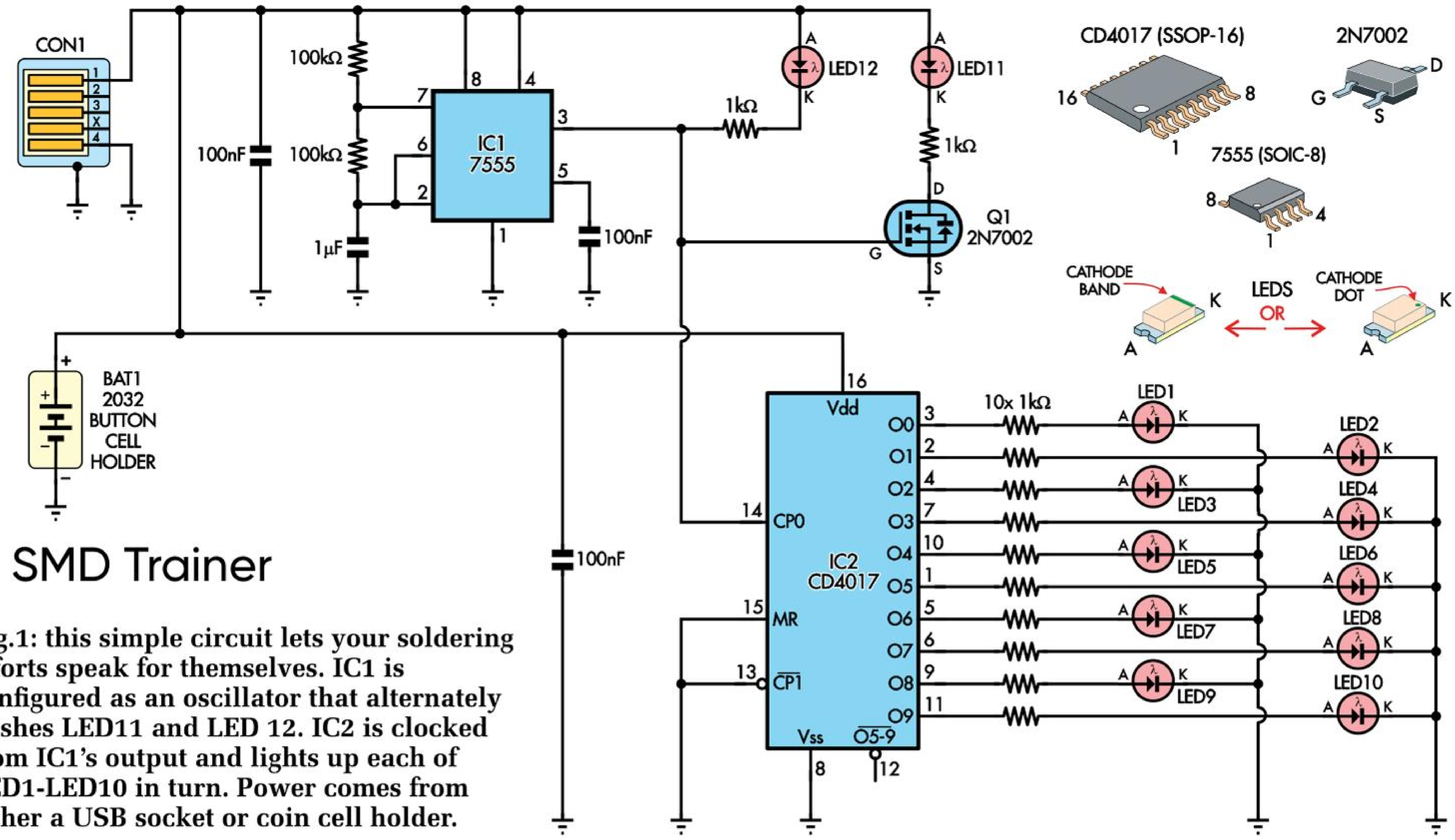
First half

IC1 is a timer IC (a 7555). We've chosen this CMOS variant rather than the bipolar transistor-based 555 to allow the circuit to work at low voltages and be powered by a coin cell. The supply passes to IC1's pin 8 (positive) and 1 (negative). Pin 4 (RESET) is held high to allow the timer to run.

IC1 has its supply bypassed by a 100nF capacitor and a second 100nF capacitor stabilises the internal voltage on the CV pin (pin 5). IC1 is configured with the 100kΩ resistors and 1µF capacitor in the well-known astable oscillator configuration.

In this arrangement, the 1µF capacitor charges from the supply via the two 100kΩ resistors; its top is connected to input pins 2 and 6. When pin 2 rises above 66% of the supply voltage (about 2V), an internal flip-flop toggles and pin 7 is connected to ground (through a transistor inside IC1). At the same time, pin 3 goes low.

This causes the 1µF capacitor to discharge through the lower 100kΩ resistor into pin 7, until the voltage on the capacitor reaches 33% of the supply (about 1V). The flip-flop resets, pin 3 goes high, pin 7 stops sinking current, the capacitor begins charging again, and the cycle repeats.


CON1
1
2
3
X
4
100nF
100kΩ
100kΩ
1µF
IC1
7555
7
8
4
6
2
3
5
1
100nF
1kΩ
A
K
LED12
LED11
1kΩ
D
G
S
Q1
2N7002
+
BAT1
2032
BUTTON
CELL
HOLDER
–
CD4017 (SSOP-16)
16
8
1
2N7002
D
G
S
7555 (SOIC-8)
8
4
1
CATHODE
BAND
LEDS
OR
CATHODE
DOT
K
A
100nF
16
Vdd
14
CP0
15
MR
13
CP1
IC2
CD4017
Vss
O5-9
8
12
O0
O1
O2
O3
O4
O5
O6
O7
O8
O9
3
2
4
7
10
1
5
6
9
11
10x 1kΩ
LED1
LED2
LED3
LED4
LED5
LED6
LED7
LED8
LED9
LED10

SMD Trainer

Fig.1: this simple circuit lets your soldering efforts speak for themselves. IC1 is configured as an oscillator that alternately flashes LED11 and LED 12. IC2 is clocked from IC1's output and lights up each of LED1-LED10 in turn. Power comes from either a USB socket or coin cell holder.

With the provided component values, the oscillator frequency is around 4.8Hz with a 66% duty cycle at pin 3 (ie, pin 3 is high about 2/3 of the time).

When pin 3 is low, current is sunk from the supply via LED12 and its 1kΩ series current-limiting resistor, causing it to light. When pin 3 is high, MOSFET Q1 is switched on by the positive voltage at its gate, and current flows through LED11 and its series resistor instead. Thus, these two LEDs flash alternately.

This first part of the circuit is built from larger SMD parts, like those we usually include in our projects when through-hole parts are unsuitable. It can operate independently of the remainder of the circuit, and can be built and tested as the first part of a two-part challenge.

Second half

A horizontal line on the PCB divides it neatly into two distinct parts; part two is below this line.

IC2, a 4017-type decade counter, is the heart of the second part of the circuit. It is powered from the same supply as IC1, connected to its pin 16 (positive supply) and pin 8 (negative supply). Its supply is also bypassed by a 100nF capacitor for stability.

IC2 has ten outputs at pins 3, 2, 4, 7, 10, 1, 5, 6, 9 and 11. These are driven high, one at a time, in response to a clock signal applied to pin 14. This signal comes from pin 3 of IC1 mentioned above. Pins 13 and 15 are pulled low to allow normal counting operation. Pin 12 is a carry output, which can be cascaded to other chips, but is left disconnected in this case.

Each of the ten outputs noted above has a 1kΩ series resistor and LED connected to its output. Thus, a clock signal at pin 14 causes the LEDs to light up in order, one at a time.

The components around IC2 have a variety of sizes to present a more interesting challenge; IC2 is also in a smaller SMD package than IC1. See Table 1 for more details.

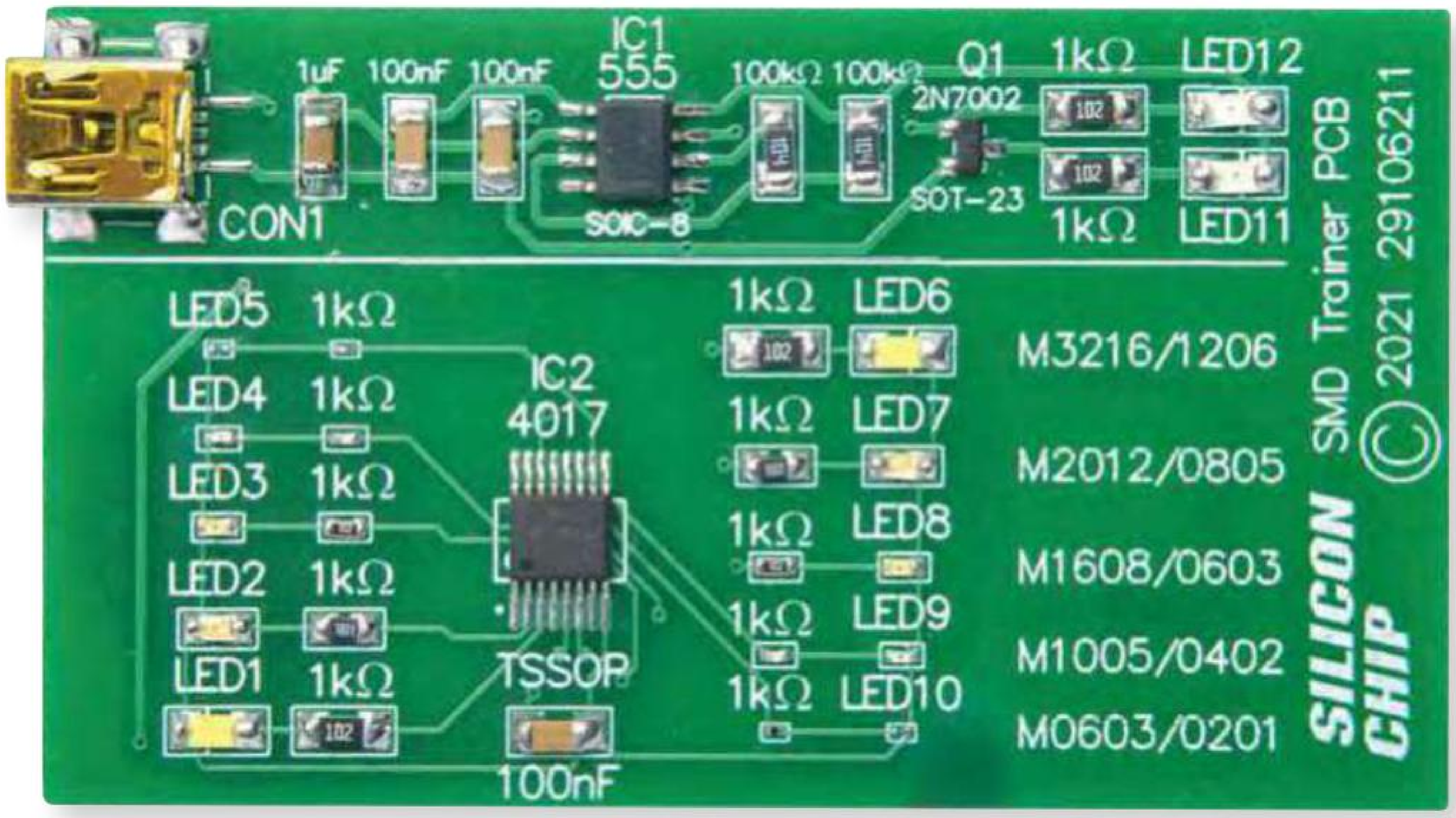
Placement and order

Our recommended assembly order for most through-hole designs is for a few reasons. Working by component type, for example, starting with resistors, then diodes, capacitors and then ICs, makes it easier to keep track of what step you are up to.

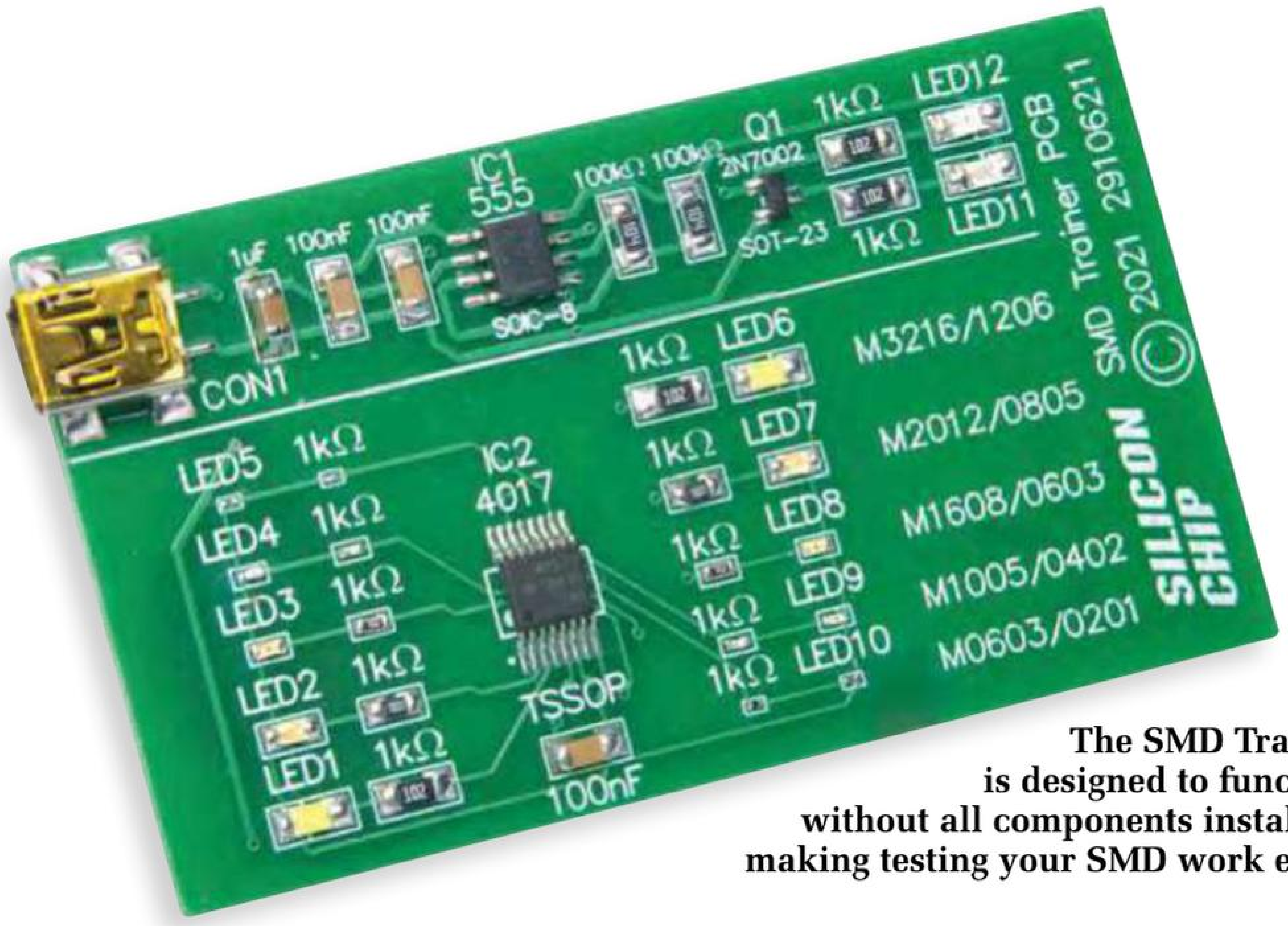
For the most part, this order is dictated by the component heights. Components that are close to the PCB are placed first as they don't restrict the placement of taller parts. Also, this means that the PCB can be turned upside down without the through-hole components falling out; they are held on the PCB by the work surface.

Working with SMD parts has similar motivations, but there is much less need to invert the PCB, so no real chance of parts falling out. Also, most SMD parts have a low profile.

Therefore, in SMD assembly the primary consideration will be to place the more difficult-to-


1uF
100nF
100nF
IC1
555
SOIC-8
100kΩ
100kΩ
Q1
2N7002
SOT-23
1kΩ
1kΩ
LED12
LED11
CON1
LED5
LED4
LED3
LED2
LED1
1kΩ
IC2
4017
TSSOP
100nF
LED6
LED7
LED8
LED9
LED10
M3216/1206
M2012/0805
M1608/0603
M1005/0402
M0603/0201
SMD Trainer PCB
29106211
© 2021
SILICON CHIP

This is the SMD Trainer board that we put together (shown at approximately 166% actual size). If you're having trouble making out the M0603/0201 LEDs, it might be because they're not fitted! We couldn't solder these by hand, and won't pretend that it's easy to do so.


CON1
1µF
100nF
100nF
IC1
555
SOIC-8
100kΩ
100kΩ
Q1
2N7002
SOT-23
1kΩ
1kΩ
LED12
LED11
SMD Trainer PCB
© 2021 29106211
LED5
LED4
LED3
LED2
LED1
1kΩ
IC2
4017
TSSOP
100nF
LED6
LED7
LED8
LED9
LED10
M3216/1206
M2012/0805
M1608/0603
M1005/0402
M0603/0201
SILICON CHIP

The SMD Trainer is designed to function without all components installed, making testing your SMD work easy.

access or difficult-to-solder parts first, so that they aren't impeded by parts fitted later.

With this in mind, the best way to construct hybrid circuits (that have both through-hole and SMD parts) is to fit the SMD parts first. Whether they are on the same side or not, the taller through-hole parts will be a greater impediment to construction if they are fitted before the smaller SMD parts.

This also means that the process of placing ICs last is no longer appropriate. Nowadays, ICs tend to be more rugged and less prone to damage from static, which was usually the motivation to fit them as late as possible.

In SMD designs (or at least those intended to be hand-soldered), the ICs typically have finer leads and are harder to work with. So it makes sense to do them first and then work on their surrounding passive components, which are often larger.

Assembling the SMD Trainer

Refer now to the PCB overlay diagrams, Fig.2 and Fig.3, which show which components go where. The SMD Trainer PCB is double-sided, measures 70.5 x 40mm, coded 29106211 and available from the PE PCB Service as just a board or a kit.

We recommend starting with the USB socket if you will be fitting it. The leads are not too small, but they are not very accessible. Fortunately, this part has locking pins on the underside that go into holes in the PCB. So positioning the part correctly is easy.

Place flux on all the pads for the USB socket and press the part down. For this application, only the two outer pads of the five are needed to supply power; hence they are the only ones that are extended. You can add more flux to the top of the pads too.

Clean the iron's tip, apply a small amount of solder and press the iron against the PCB pad. If the solder doesn't run onto the lead, bring it closer, until it is touching if necessary. Repeat for the other outer pad.

With this connector, make sure you don't touch the iron against the USB socket shell when making these power connections. The tight angle here is what makes this tricky. If you form a bridge, apply heat to all the pins to remove the part and tidy both the socket and PCB with solder braid.

For the larger pads that secure the USB socket mechanically, simply apply the iron, add some solder until a tidy fillet forms, then remove the iron. A generous amount of solder here will result in a secure connection.

Using a similar procedure, place IC1 and Q1, ensuring that they are oriented correctly. Then solder the resistors and capacitors in place. Note that there are two different values of each – refer to our photos.

The LEDs are also polarised, and must be fitted with their cathodes to the left towards the resistors.

If you wish to fit the cell holder instead of the USB socket, do so now. It's usually easier to fit parts on one side of the board at a time, but this will allow you to test out the first part of the circuit that you have just assembled.

Flip the PCB over and put some flux on the two smaller outer pads. Leave the large inner pad clear, as the PCB pad itself becomes the negative terminal and doesn't need soldering.

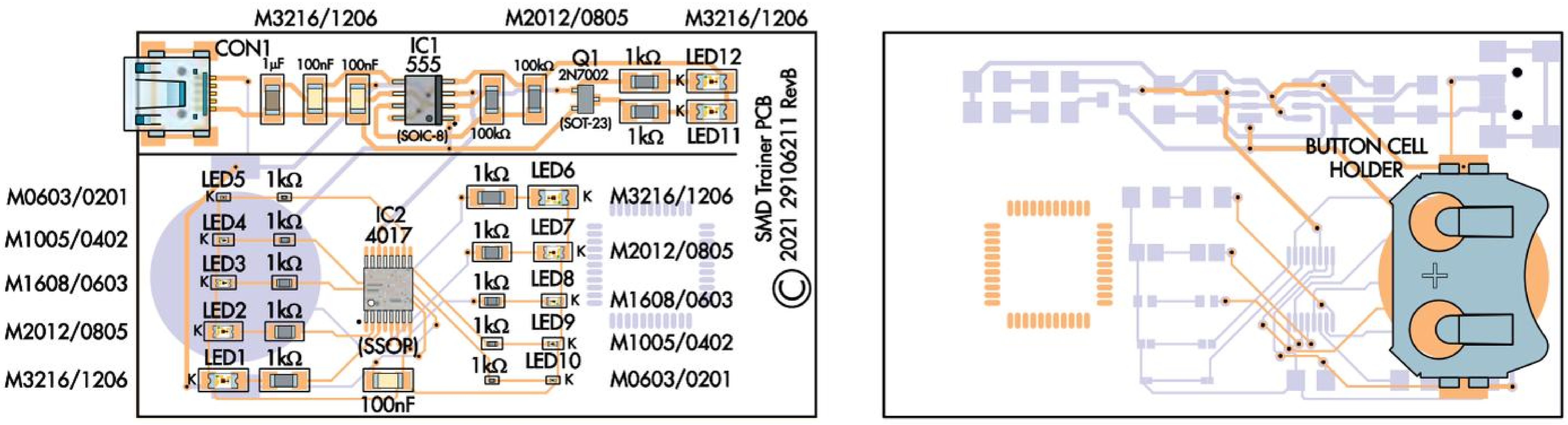
Also ensure that the holder opening is towards the edge of the PCB, so that you can easily insert the cell. Position the holder roughly in place and add some flux to the top of the leads.

Note that, unlike the USB socket, there is nothing to lock this part in place on the PCB.

You will probably need to turn up the temperature on the iron slightly (if it's adjustable) and load some solder onto the tip; a bit more than for the smaller parts. Use tweezers to keep the cell holder in place and touch the iron to the pad.

Give it some time to heat up; remembering that it is all one piece of metal, so it is unlikely to be damaged by too much heat. You should see the flux smoke and the solder flow. Remove the iron and give the part (and solder) a few seconds to cool before releasing the tweezers.

The first joint doesn't need to be perfect; the main thing is that the


M3216/1206
M2012/0805
M3216/1206
CON1
1µF
100nF
100nF
IC1
555
(SOIC-8)
100kΩ
100kΩ
Q1
2N7002
(SOT-23)
1kΩ
1kΩ
LED12
LED11
K
SMD Trainer PCB
© 2021 29106211 RevB
M0603/0201
M1005/0402
M1608/0603
M2012/0805
M3216/1206
LED5
LED4
LED3
LED2
LED1
1kΩ
IC2
4017
(SSOP)
100nF
LED6
LED7
LED8
LED9
LED10
M3216/1206
M2012/0805
M1608/0603
M1005/0402
M0603/0201
BUTTON CELL HOLDER
+

TOP OF PCB

BOTTOM OF PCB

Figs.2 and 3: start by fitting the components in the top half of the PCB, which forms the alternate flasher, lighting LED11 and LED12. These components are larger SMDs that are generally not too hard to solder. Once you have those working, you can move onto the more challenging parts below, which form an LED chaser. With IC2 and its bypass capacitor in place, fit LED1, LED6 and their series resistors, then move onto the smaller parts, testing it at each step to ensure your soldering is good.

part is accurately positioned and held firmly in place.

The second pad can be approached like the larger pads on the USB socket. Apply the iron, feed in the solder until a good fillet is formed, then remove the iron. Give it a few seconds to solidify before returning to the first pad to make it tidy. You can touch it up by applying the iron and solder in the same fashion.

Parts List – SMD Trainer

1 double-sided PCB coded 29106211, 71 x 40mm, available from the *PE PCB Service*
1 mini-USB socket (CON1) ***OR***
1 SMD coin cell holder (BAT1) **[BAT-HLD-001; Digi-Key, Mouser etc]**

Semiconductors
1 7555 CMOS timer IC, SOIC-8 (IC1)
1 4017B decade counter IC, SSOP-16 (IC2)
1 2N7002 N-channel MOSFET, SOT-23 (Q1)
4 M3216/1206 size LEDs, any colour (LED1, LED6, LED11, LED12)
2 M2012/0805 size LEDs, any colour (LED2, LED7)
2 M1608/0603 size LEDs, any colour (LED3, LED8)
2 M1005/0402 size LEDs, any colour (LED4, LED9)
2 M0603/0201 size LEDs, any colour (LED5, LED10)

Capacitors *(all SMD X7R 10V+ ceramic)*
1 1μF M3216/1206 size
3 100nF M3216/1206 size

Resistors *(all SMD 1% or 5%)*
2 100kΩ M3216/1206 size
4 1kΩ M3216/1206 size
2 1kΩ M2012/0805 size
2 1kΩ M1608/0603 size
2 1kΩ M1005/0402 size
2 1kΩ M0603/0201 size

SMD Trainer kit

We can sell you just the PCB or we have a limited run of a kit of parts to build the SMD Trainer Board with everything except the coin cell (CR2032 type), which is widely available. Altronics also has a kit for this project, code K2001, at around £15 PLUS p&p – see: www.altronics.com.au

Initial testing

The first part of the circuit should now work. You can test it by fitting the button cell or applying power from a USB source. If using the button cell, ensure the polarity is correct. You should see LED11 and LED12 flicker alternately.

If one LED is stuck on, then IC1 is not oscillating, and you should check it and the components around it. If only one LED is flashing, the other might not be soldered correctly; this could include either of the 1kΩ resistors or Q1.

You might also see what appears to be the two LEDs on at the same time. In that case, they are probably flashing faster than the eye can see. One possible reason for this is that the 1μF timing capacitor has been mixed up with one of the 100nF capacitors.

At this point, it's best to verify that this part of the circuit works correctly. Otherwise, if the second part doesn't work, it will be harder to determine the problem.

Remainder of the circuit

You'll note that the components in the lower half of the PCB are fairly well spread out. This is a luxury that won't be present in all SMD designs.

With the amount of space present on the *SMD Trainer Board*, it's certainly possible to install these components in just about any order. But we recommend starting with IC2 and its capacitor, followed by the LEDs in order of size from largest to smallest. This will allow you to power up the circuit at any time after you have any of the larger LEDs fitted, and check that it is working.

Start with IC2. Apply flux and position the part. We've been quite generous with the length of the pads here, for two reasons.

First, we have seen SOP variants of this part being available with various body widths. So this pad configuration offers the flexibility to accept a range of compatible parts. Second, it makes it easier to solder.

Clean the tip of the iron and add a tiny amount of fresh solder to it. Hold IC2 with the tweezers and apply the iron to the PCB pad only. You should see the solder flow onto the lead and form a joint strong enough to hold the part in place.

Check that the leads are aligned and solder the remaining pins in this fashion. These tiny parts do not need much solder, so you might find that you only need to occasionally add solder to your iron.

Check for bridges and rectify as needed. Follow with the remaining 100nF capacitor. LED1 and LED6 are M3216/1206 sized parts, so you should be comfortable fitting them and their respective 1kΩ resistors. Note that all cathodes are on the side away from IC2.

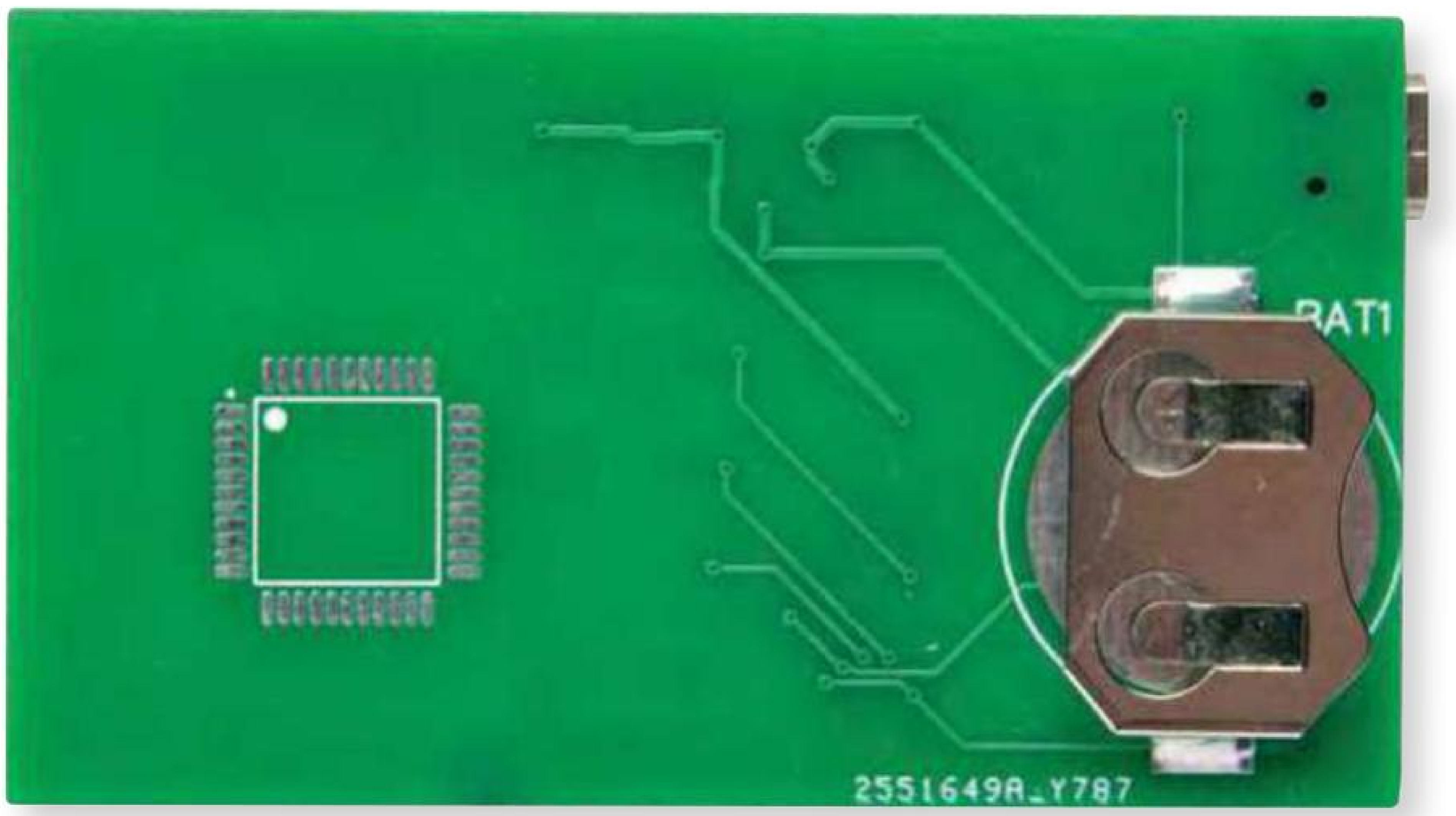
And test again

Our design is incrementally functional, so you can power and test the partially completed design at just about any time. You should see LED11 and LED12 continue to alternate as before; if they do not, then you might have a short circuit that is shunting power away from IC1 and its components.

LED1 through to LED10 should flicker on and off in turn when fitted. If you get nothing at all, check that IC2 is fitted correctly, with the correct orientation and no bridges. Individual LEDs not flashing are probably a sign that a single LED or its resistor are not fully soldered.

Completion

Take your time and work through the differently-sized LEDs and resistors in turn. Don't be disappointed if you can't solder the M1005/0402 or M0603/0201 parts by hand. We have not used anything smaller than M1608/0603 in any of our designs, and even we find anything smaller than M1005 challenging.



There's a set of TQFP pads located on the underside of the PCB. This is for you to practice soldering, and does not have any electrical connection to the circuit.

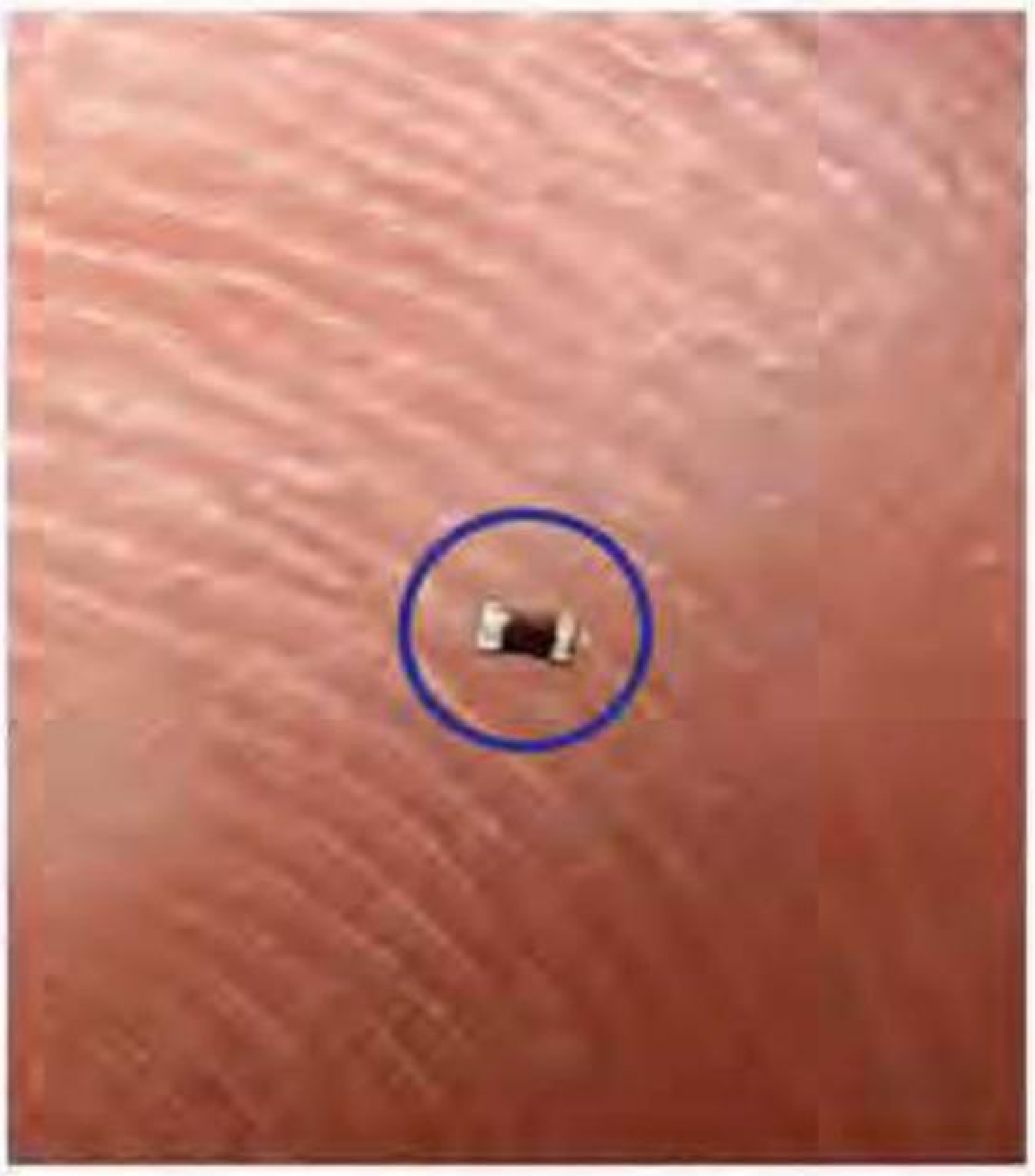
Table 1 – common passive SMD component sizes

Metric	M3216	M2012	M1608	M1005	M0603	M0402
Length	3.2mm	2.0mm	1.6mm	1.0mm	0.6mm	0.4mm
Width	1.6mm	1.2mm	0.8mm	0.5mm	0.3mm	0.2mm
Imperial	**1206**	**0805**	**0603**	**0402**	**0201**	**01005**
Length	0.12in	0.08in	0.06in	0.04in	0.02in	0.01in
Width	0.06in	0.05in	0.03in	0.02in	0.01in	0.005in

Anything that tiny is not intended to be soldered by hand. The smaller LEDs often have exposed pads only on the underside, making it very difficult to transfer heat where it is needed.

There are some tricks you can use, such as applying a small amount of solder to the pads and trying to conduct heat through the PCB trace radiating out from the lead. Or try your hand at reflowing solder using hot air or infrared.

We published a *DIY Solder Reflow Oven* design in the April and May 2021 issues. It is also possible to successfully reflow a board with 'tools' such as electric frypans and clothes irons!



This M0603-sized component, shown on a fingertip, measures a miniscule 0.6 x 0.3mm, making it easy to lose.

Cleaning

Once you are satisfied with your progress, clean up any residual flux and allow the board to dry fully. Although the board doesn't do anything incredibly useful, it is still a handy reference tool and will remind you of the tricks and techniques you learned when constructing it.

Further reading

We have, of course, written articles in the past about surface-mount technology, devices and construction. You will find these useful:

- **How to Solder Surface-mount Devices**
  July 2010
- **PIC n' Mix: Building circuits with SMDs – Parts 1 and 2**
  February and March 2019
- **A DIY Reflow Oven Controller for modern soldering**
  April and May 2021

Complete kit

We offer either just the PCB or while stocks last, a complete kit of parts (go to the *PE PCB Service*) – see the parts list.

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SMD Soldering Tips & Tricks

By Tim Blythman

While the only differences between SMD and through-hole components is packaging and how they are soldered to the PCB, there is a lot of jargon surrounding SMDs and new techniques required to work with them, especially the smaller types. This article accompanies our SMD Trainer project and provides a lot of detail to help you become an SMD soldering master.

Image source: www.pxfuel.com/en/free-photo-qhfan

Undoubtedly, some people would prefer to learn how to solder SMDs by getting a hold of the *Trainer* board (see page 36) and some parts and just getting stuck into assembling it. However, soldering SMDs is a lot easier if you know the tricks.

You might find the information in this article helpful even if you don't plan on building the *SMD Trainer*. There's plenty of general advice and hints here, so it's well worth a read. However, keep in mind that this article is intended to accompany the *Trainer*; it does not describe less common components and SMD packages that do not appear on the *Trainer* PCB.

If you have some SMD experience but still might have something to learn, you could read through this article and skip over any sections about subjects that you already understand.

SMD component sizes and packages

Many of the components used in our *Trainer* design (including the resistors, capacitors and diodes) have two leads (terminals) and are in so-called 'chip' style packaging. These are small, flat and roughly rectangular. These tend to be the most numerous type of components in any design based primarily on surface-mount parts.

Some passive components come in different types of SMD packages. For example, it's common to see small electrolytic can capacitors sitting on a small plastic base with SMD-style leads protruding. While smaller than most electros, they are still larger than most surface-mount passives, so they are not hard to work with.

The parts in chip packaging are often described by a four to six-digit code, and there are both imperial and metric versions of this code. For example, a common 3216 metric sized part would be interchangeably known as 1206 under the imperial system. Confusingly, there are some parts with the same codes in both systems (including 1206), but they are very different sizes!

One way of differentiating these is to use the 'M' prefix for metric sizes; this is what we prefer, and we will usually quote both to resolve ambiguity. For example, you will often see (M3216/1206) in our parts lists. This is the largest resistor and capacitor size that we have used in the *SMD Trainer*. Larger parts are available, though; the next step up is usually M3226/1210 and then M4532/1812.

The first two digits determine the component length, while the other digits determine the width. Most parts are longer than they are wide, so the first two digits will be greater, but this is not always the case. Usually, the leads are along the short sides, but in cases where the leads span the longer sides, the numbers might be reversed (eg, M1632/0612).

The metric digits are in tenths of a millimetre, so an M3216 part measures 3.2mm long by 1.6mm wide. Also note that the two terminals will be situated at opposite ends, lengthwise.

Under the imperial system, each pair of digits accounts for 1/100th of an inch, so a 1206 part is 0.12in by 0.06in, close to the metric equivalent.

Table 1 summarises some of the more common two-lead sizes. Note the last row showing a five-digit imperial code (with a dimension under 1/100th of an inch or 0.25mm!). You can also see how, confusingly, some codes (such as 0603 and 0402) are present in both rows.

On our *Trainer* board, the parts around IC1 are all M3216/1206 size. This is one of the largest sizes for which there is a comprehensive range of parts, so it is a good choice for using SMD parts where there is no need to go smaller.

The LEDs around IC2 vary from M3216/1206 through M2012/0805, M1608/0603 and M1005/0402 down to M0603/0201. Each has a corresponding resistor of the same size.

Another two-lead package that you might see is often used for diodes and is known as SOD-123 (small outline diode). These are similar in appearance to the transistor packages we'll describe below, but only have two leads.

Components with three or more leads

IC1 and Q1 on our board are also in commonly-available SMD packages.

For parts with more than two leads, there are often variants with differing pin counts but otherwise identical pin pitch and spacing between rows. Parts called SOIC or SOP (small outline IC or small outline package) typically have pins with 1.27mm or 0.05in pin pitch.

This is exactly half the pitch of most DIL (dual in-line) through-hole parts. IC1 is in a SOIC-8 package with a 3.9mm body (plastic part) width. Like DIL parts, width tends to increase as the pin count increases, to allow room for the internal leads to fan out along with larger silicon dies.

The package we have chosen for transistor Q1 is called SOT-23 ('small outline transistor'). There are also variants with extra pins opposite each of these, called SOT-23-6, plus SOT-23-5, which is much the same as SOT-23-6 but lacking a middle pin on one side (see Fig.1 below).

The basic SOT-23 parts (MOSFETs, small-signal transistors, dual diodes...) are quite easy to work with, as they will only fit their pads one way, and the pins are fairly well spaced and accessible. But they are getting to the point where their size means they are more likely to be misplaced, lost or simply fly into the distance without a trace if not handled carefully.

A clean workspace of uniform colour is the best strategy against losing these tiny parts.

The package size of IC2 on our Trainer board is the next step down, called SSOP for 'small shrink outline package'. You'll also see these with other modifiers, such as TSSOP (thin small shrink outline package). Either way, they'll have a 0.65mm pin pitch, about half that of SOIC. Besides being thinner, TSSOP packages are also narrower than SSOP, so watch out – some footprints will suit either, but not all.

Table 1 – common passive SMD component sizes

Metric	M3216	M2012	M1608	M1005	M0603	M0402
Length	3.2mm	2.0mm	1.6mm	1.0mm	0.6mm	0.4mm
Width	1.6mm	1.2mm	0.8mm	0.5mm	0.3mm	0.2mm
Imperial	**1206**	**0805**	**0603**	**0402**	**0201**	**01005**
Length	0.12in	0.08in	0.06in	0.04in	0.02in	0.01in
Width	0.06in	0.05in	0.03in	0.02in	0.01in	0.005in

Integrated circuit packages

Another common IC package that is suited to hand-soldering is the QFP (quad flat pack) and its many variants, such as TQFP (thin quad flat pack). These come with a variety of pin pitches, with 0.8mm down to 0.4mm being typical.

They are often used where more pins are needed in a small space, such as for microcontrollers. While the packages are not much smaller, with the pins arranged around four of the sides, they can be more tricky to align correctly.

We've placed a QFP-44 (10x10) footprint on the rear of the PCB for reference; it has 44 pins (11 along each side), while 10x10 refers to the plastic case dimensions in millimetres. It has a pin pitch of 0.8mm. You can test your skills if you have a suitable part, although it won't do anything. It could also be useful as a reference for checking dimensions and pin pitches.

While it's usually the tiny size of SMD parts that makes hand-soldering difficult, there are other reasons too. For parts smaller than SSOP, a designer might choose a QFN (quad flat no-lead), BGA (ball grid array), VTLA (very thin leadless array) or WLCSP (wafer level chip scale packaging).

These parts are not intended to be soldered by hand; they depend on a reflow process or similar to be soldered correctly. That's not to say that they can't be hand-soldered at all, but it is very difficult.

Some parts can also have large 'thermal' pads on the underside of their packages that need to be soldered. Unless the PCB is designed with a via through the PCB to allow the solder to be fed from the other side, it isn't practical to solder these by hand either (although a handheld hot air reflow tool can be used with great success).

The packages and parts described so far are all standard to a degree. There are also numerous SMD parts that come in unique packages. Our *SMD Trainer* has two parts like this; the mini-USB socket and the coin cell holder.

SMD component markings

Markings on SMD parts can be cryptic, even when present, but resistors (above a certain size) are thankfully quite straightforward.

Instead of a colour code, they are simply printed (or laser etched) with the numeric equivalent of the colour code. A through-hole 10kΩ resistor would have coloured stripes of brown, black, orange or brown, black, black, red, indicating 10 followed by three zeroes or 100 followed by two zeros.

An SMD 10kΩ resistor would simply be marked '103' or '1002'. Note that there is no tolerance code.

Unfortunately, the common ceramic chip SMD capacitors are not usually marked at all. In this case, all you can do is make sure that the parts are well labelled in their packaging and only work with one value at a time.

ICs can be tricky, too, as they usually have cryptic codes etched into the smaller space that's available on their tops. SOIC parts may be large enough to have a sensible code, but SOT-23 parts are too small for this. Some manufacturers may even use the same code that another manufacturer has used for a different, incompatible part. The part's data sheet usually indicates what code(s) they have used.

ICs also have a mark indicating their orientation. Usually, the marking is

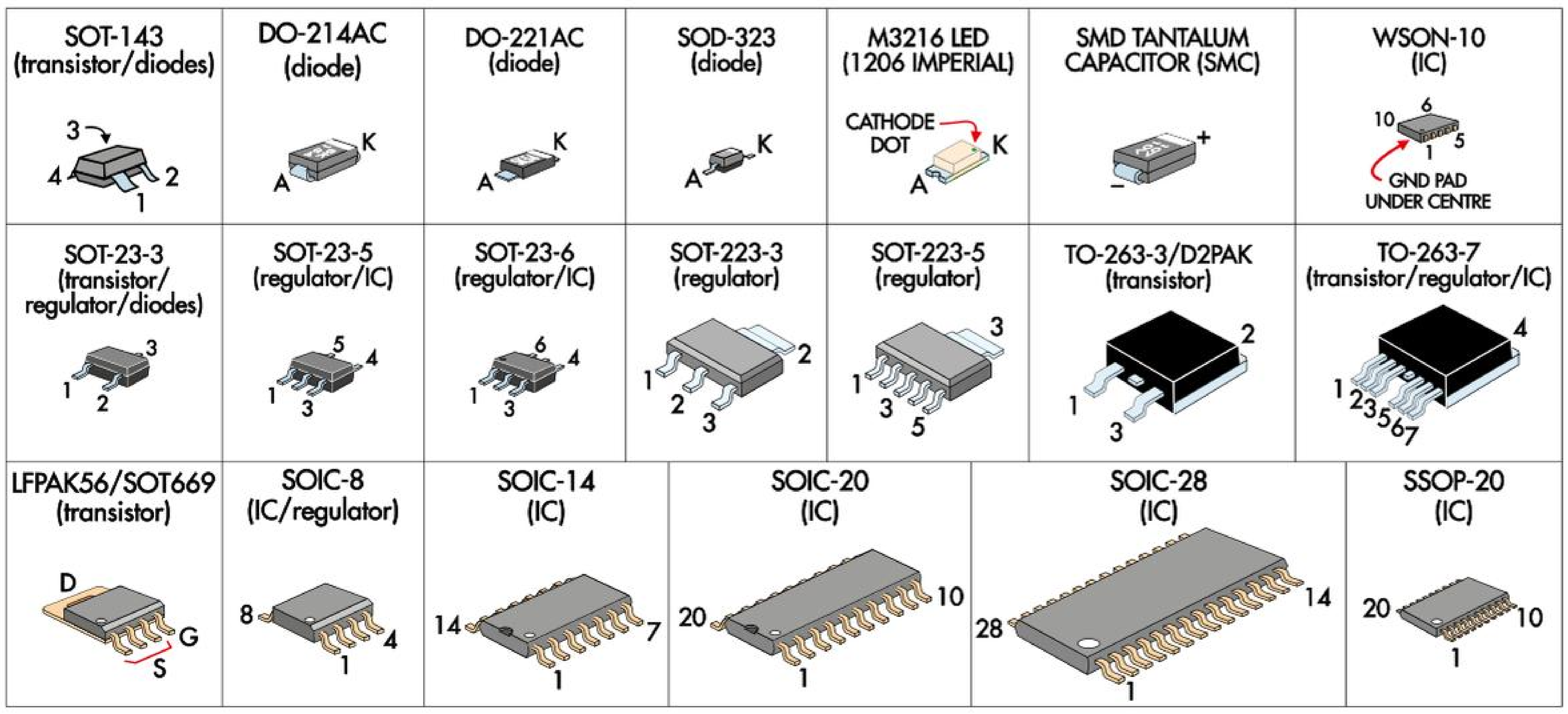


Fig.1: some of the more common surface-mount component footprints are shown at left (eg, SOT-23, SOIC-8, SSOP-16, M3216/1206) along with pin numbering.

intended to highlight pin 1. This may be a dimple in the plastic moulding or a bevel along one edge. Or it might be an etched symbol on the part top.

Referring to the data sheet is the best way to find out what this mark will be. We usually mark the location of pin 1 on the PCB silkscreen with a small dot or '1'.

Some SOIC parts will have a notch and bevel marked on the silkscreen too, corresponding to these features that might exist on the IC. Note, though, that different manufacturers of equivalent parts can use different methods for indicating pin 1.

Since the smallest SMD components are not intended to be placed by hand, they generally have no distinct markings. Instead, a computerised pick and place machine is programmed to know how they are oriented in the tape reel on which they are supplied; the data sheet will often show this.

As LEDs are polarised, they too usually have a polarity mark. It can vary, but it is usually a green dot or T-shape marking the cathode, or a small triangle that matches the direction of the triangle in the diode symbol and thus also points to the cathode.

Tools and consumables

This article is intended for relative beginners, so we will assume you mainly have tools intended for soldering through-hole parts. That means a soldering iron (temperature-controlled ideally) and some solder wire. You could use those tools to assemble the first section of our *SMD Trainer Board* with a bit of care, although a few extra items will be helpful.

Tweezers

You'll need something to hold the parts in place while soldering. The small size means that you can't use your fingers; even if they were small enough, they would get burnt very quickly! Fine-tipped tweezers are ideal.

To get an idea of what you need, check out kits like Jaycar's TH1752 or Altronics' T2374, which are perfectly adequate, although precision points can be helpful for smaller parts. Just about anything that can be described as tweezers will be better than nothing.

Flux

Practically all electronics solder contains flux or resin, usually sufficient for through-hole construction. But you probably won't realise the benefits that a separate flux can bring until you start using it.

While you might be used to solder wire 'just working', it's actually the resin core (the resin from certain trees makes an excellent flux) that is largely responsible for this. There are other, more modern and even synthetic fluxes, but resins (called 'rosins' after purification) continue to be used as they are quite effective.

If you've ever tried reusing solder, you'll know that it doesn't work as well as new solder. That isn't due to its age, but because the flux has been consumed.

This is primarily due to the metal oxides that build up over time as metals react with oxygen in the air. One feature of flux is that it is a reducing agent; the simple explanation of this property is that it can reverse oxidation.

The flux reacts with the oxides to leave a pure metal that will bond better. Many fluxes also form a layer to keep out oxygen and prevent further oxidation, which also applies to the solder itself, PCB pads and component leads.

Another important feature of flux is that it should be heat-activated and only work near the soldering temperature. This prevents it from being used up prematurely.

Flux can also enhance heat transfer. Since all surfaces need to be heated above the solder melting (eutectic) point to enable good solder bonding, flux can help get heat into where it is required. The flux can be applied directly to the parts and PCB in surface-mount work, facilitating heat transfer from the soldering iron to all components.

The flux also reacts with the various oxides and contaminants to neutralise their negative effect on the soldering process. The reaction products are referred to as 'slag'. This is due to the reactions with the various oxides. The result is often a dark, sticky substance that collects on the tip of the soldering iron.

Flux can also be a potently corrosive chemical and can damage a board if any is left behind. Your flux should have a data sheet that explains this aspect in detail; those marketed as 'no-clean' are less likely to leave a corrosive residue.

Liquid fluxes, flux pens and flux pastes are available; our preference is for a paste or gel as it is easier to apply and control and sticks around longer. Even for the amount of soldering we do, a fairly small syringe lasts for years (or at least until it expires), so there is no need to buy a huge amount of flux paste.

For ease of handling, we recommend getting a small syringe, such as Altronics' H1650A Flux Gel Syringe. The syringe allows for the precise application of small amounts.

Cleaning

It's important to clean up after soldering, especially if you use a lot of flux (which is not a bad idea since it results in more reliable joints). You'll probably find that you'll need to clean your iron's tip as you go.

A cleaning sponge is the most common choice here; lightly moisten it, just enough to prevent the iron from burning the sponge. We've seen brass sponges that work pretty well, but they don't seem to have the ability to capture all the residue. In a pinch, a lightly-moistened paper towel works well.

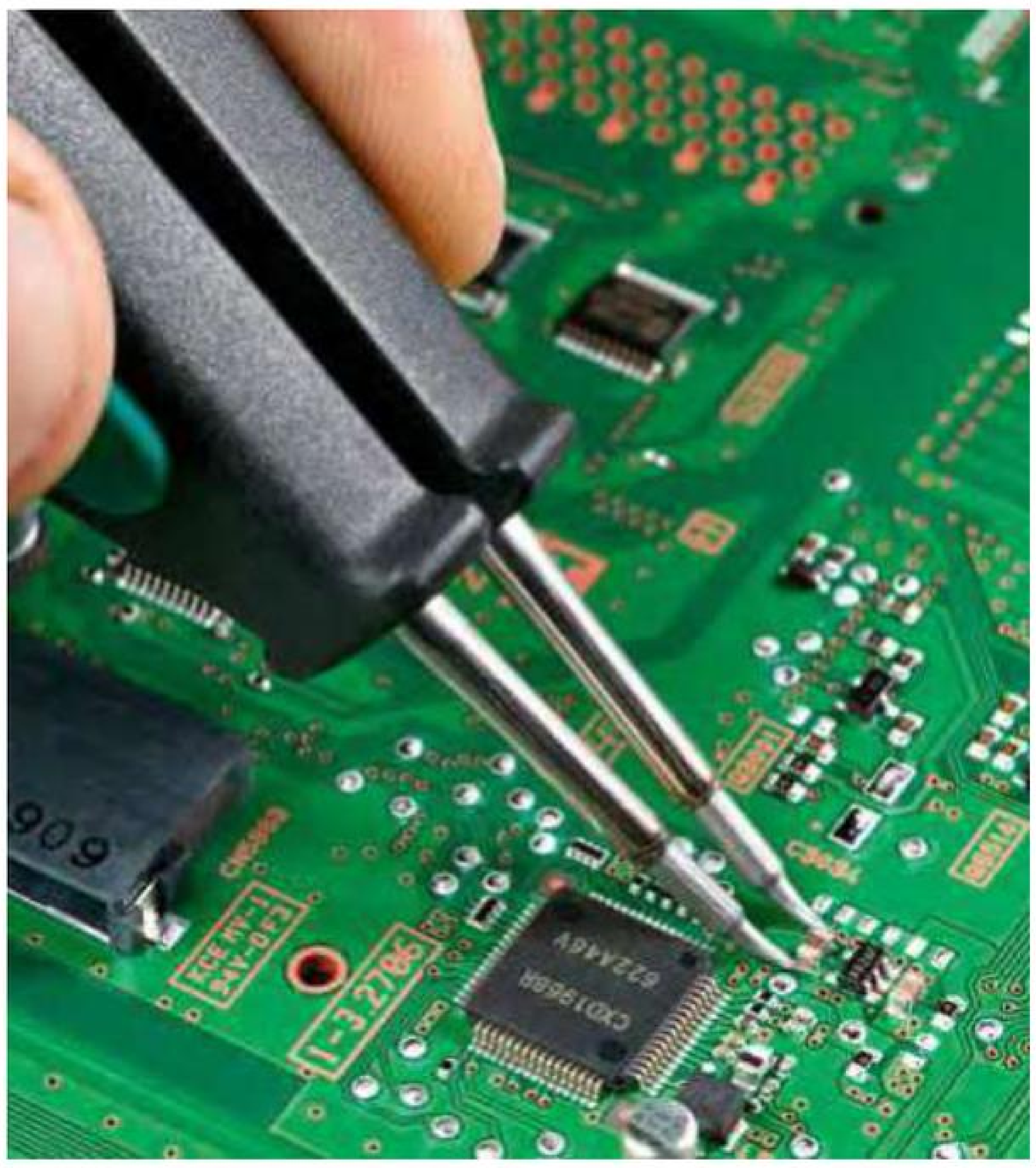
Solvents

Most fluxes will also recommend a cleaner (even the so-called no-clean fluxes). Isopropyl alcohol (isopropanol) is a reasonable all-around choice. Some fluxes and their slags are sticky and might require scrubbing to be cleaned up properly.

Therefore, an even better option is a specialised flux cleaner like Chemtools' Kleanium Deflux-It G2 Flux Remover.

Take care with these solvents. Many, including isopropyl alcohol, are flammable, while some are poisonous or can damage the skin. The solvent datasheet or MSDS is the best place to find advice and information about these things.

The presence of flux should not inhibit testing of most low-voltage circuits but must be removed from mains circuits before applying power. The impurities captured by the flux can



Tweezers are useful for holding components when soldering. You can also purchase tweezers with heating cores, which can be used for desoldering as shown in this photo.

Source: https://commons.wikimedia.org/wiki/File:Soldering_a_0805.jpg

MG Chemicals
ROSIN FLUX PEN
#835-P 10 mL, 9.3 g
DANGER
PELIGRO
PERICOLO

For applying flux there's a variety of different tools you can use, such as this flux pen above. We generally recommend using a flux gel syringe over a pen or container of paste because it's easy to apply and doesn't boil off immediately

create a conductive path that would be dangerous at such voltages.

You should also clean the flux off the PCB to be able to inspect it properly. Flux and slag can obscure solder bridges and poor solder joints. It's best to clean as you go, rather than leave it all until the end, as flux is easier to remove when warm.

Clean up using the appropriate chemicals. It's best to use Nylon brushes and/or lint-free cloths since you don't want to leave fibres behind on the board. Don't just spray or pour the cleaning solution onto the board; you need to remove it after it has had a chance to dissolve the flux. Sometimes letting it sluice off will carry away much of the flux, but you'll still need to dab it dry.

You may find that the cleaning process is imperfect or, even worse, reveals a soldering failure. There's no choice but to go back and fix the problem, then clean and inspect it again.

Solder wicking braid

You might also hear this called 'desoldering braid' or 'solder wick'; it is a length of finely woven copper wire that has usually been impregnated with some sort of flux. It is used to wick away (or absorb) excess solder.

A typical use is removing the excess solder which has formed a bridge between two pins, or cleaning solder from a pad after removing a defective part and before fitting a new part.

It is pretty cheap; you can purchase a small roll over 1m long for a pound or two from RS, Farnell, eBay, Jaycar (Cat NS3020) or Altronics (Cat T1206A). A typical use might consume a few millimetres of braid, so it too will last for quite a while.

PCB holder

Many boards that use SMDs are quite small, and it can be helpful to secure a PCB in place while working on it. It's also handy to be able to move it around to access a particular component at a certain angle.

Tool's like Jaycar's TH1982 Third Hand PCB Holder or Altronics' T2356 Spring Loaded PCB Holder are ideal. The PCB is held in place but can be adjusted, or the entire tool rotated, to allow access from different angles.

While these tools are not expensive, even something like Blu-Tack or a similar reusable putty can be a handy makeshift substitute. While the heat from the iron will likely soften and tarnish the Blu-Tack, we've never had any trouble using it to hold a PCB in place.

Magnifiers

Being able to clearly see the tiny parts and features involved with SMD projects is paramount. There are two important ways that you can improve the way you view your board: magnification and illumination.

If you have keen eyes and you're working with some of the larger parts in SOIC and M3216/1206 packages, you may well do fine without magnification. But it is still vital to peer closer to inspect your work and check that everything is as it should be.

Fortunately, there is a vast range of things that you can use for magnification, and you might well already have some of these, like a simple handheld magnifying glass.

Some PCB holders include a magnifier of some sort, including Jaycar's TH1987 PCB Holder with LED Magnifier. That one includes a soldering iron stand too.

The other extreme is a microscope. While certainly not as cheap, not much magnification is needed. Many microscopes also provide excellent illumination. These days, there are many USB and digital microscopes available.

A smartphone camera is a suitable piece of gear that most people will already have in their pocket. A digital camera with an LCD viewfinder is a similar option.

You might need to use the zoom feature (even digital zoom will be very helpful) to see a reasonable amount of detail. If your device has a macro mode, then that will be better suited for close-up viewing too.

We generally find that it's handy to have both a fixed magnifier that can be rigged up in place above a PCB, as well as a small handheld unit that can be picked up and aimed as needed.

Lighting

Good lighting is paramount for successful SMD work. A diffused light source is best, as point sources can cause shadows that obscure parts of the PCB, especially between component leads where bridges might form.

If you only have point sources, then aim them from opposite sides to cancel shadows. You can diffuse the light by reflecting it off something white like a wall, ceiling or sheet of paper.

As long as you're happy you can see what you need to see, then you probably have enough light.

Fume extractions

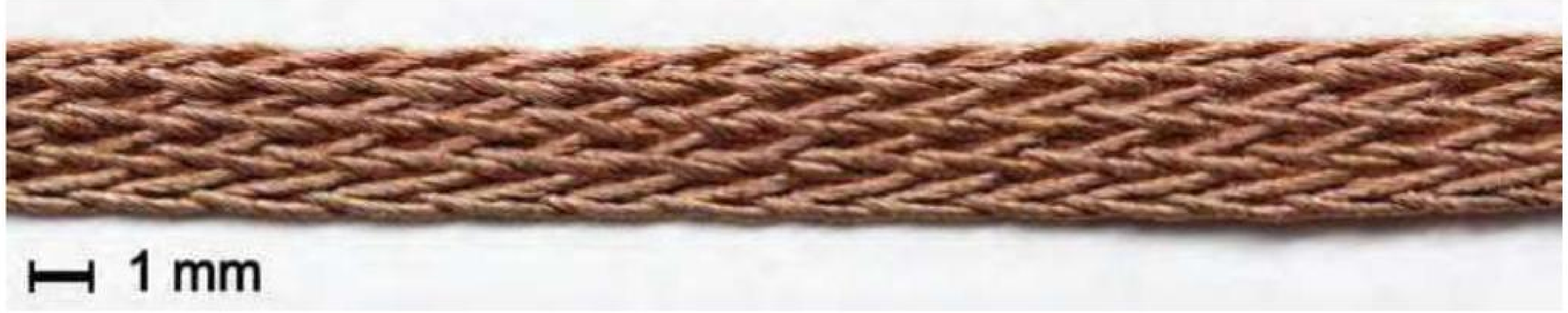
Remember that flux also generates smoke which is unhealthy to inhale. A fume extraction hood is the recommended way of dealing with this but can be expensive. A small fan (such as a computer fan) can work too, set up to blow away from you.

If you can't manage some sort of active fume control, working outside (or near a large open window) is another option.

Top gear

If you don't already have them, the items we've mentioned so far are all available at reasonably low prices. We'll also briefly touch on a few items that can further enhance your SMD experience.

We noted earlier that a basic soldering iron is probably adequate to work with larger SMD parts. When you start to get into the smaller parts,

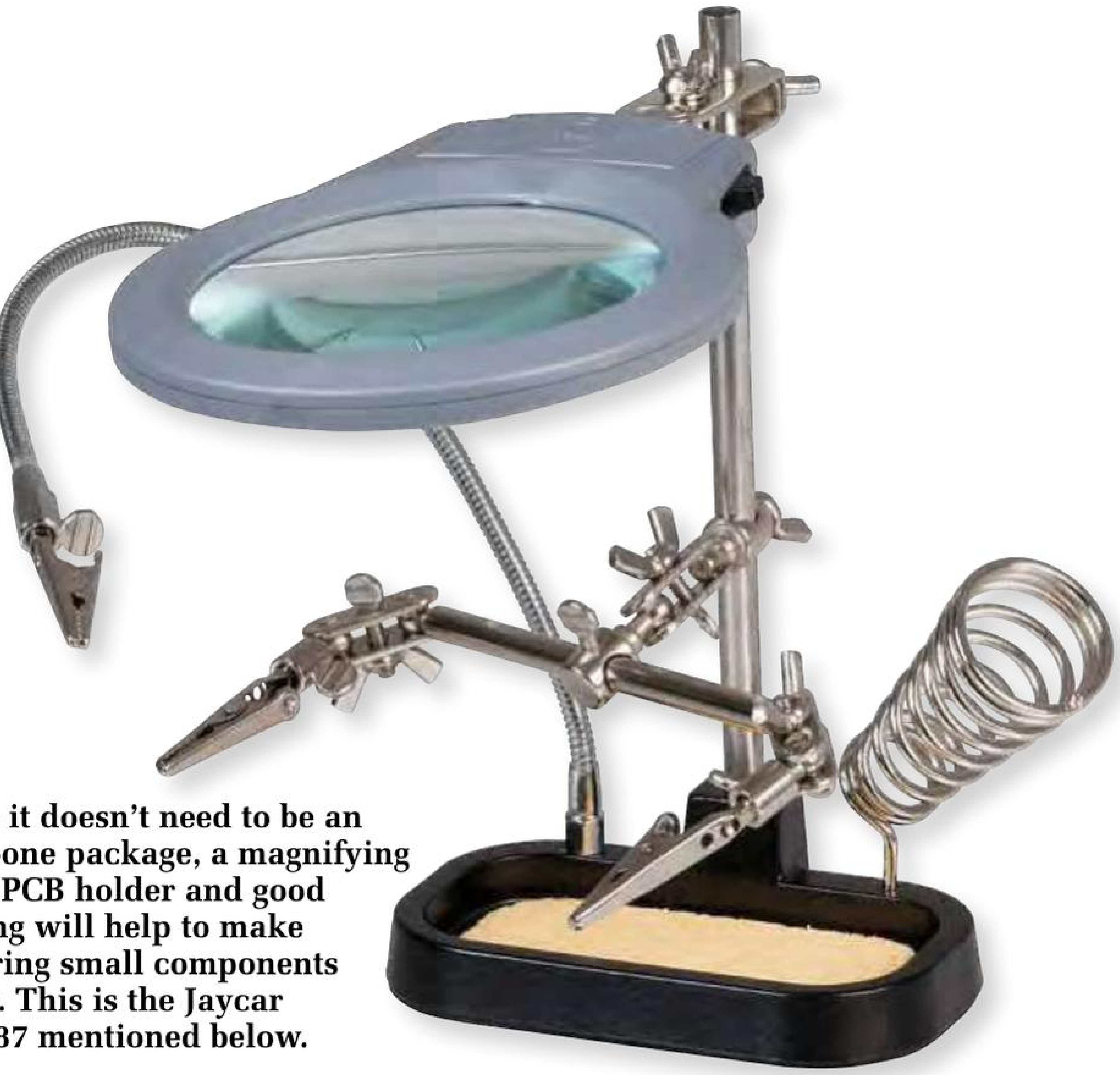


This is a close-up of some solder wick braid. It's normally sold on a reel and is used for cleaning solder.

Source: https://commons.wikimedia.org/wiki/File:Solder_wick_close_up.jpg

A solder sucker is better for removing a larger volume of solder, while a braid is better for smaller jobs such as SMD components.

Source: https://commons.wikimedia.org/wiki/File:Solder_sucker.jpg



While it doesn't need to be an all-in-one package, a magnifying glass, PCB holder and good lighting will help to make soldering small components easier. This is the Jaycar TH1987 mentioned below.

then some optional features defintiely become essential.

Two aspects will help. A fine tip will allow more accurate soldering as you generally want to make contact with just one pin at a time (but see the section below about drag soldering; larger tips can be better with those techniques). The edge of a chisel tip can be narrow enough to work down to relatively small sizes.

A soldering station with adjustable temperature is an advantage when working on larger parts. Many of these come with stands and sponges, which also help.

Finally, a hot air rework gun can be very handy for desoldering SMDs or reflow-soldering some of the trickier parts. These are available at surprisingly low prices and are well worth having if you plan to do much work with surface-mount components.

Using your tools

To sum up the advice given above, make sure you have some flux paste, a soldering iron tip-cleaning sponge and some appropriate solvent for your chosen flux. Use the flux generously and keep your iron's tip clean.

Soldering techniques

If you've read any of our SMD construction articles before, then the following will be familiar. We'll even go into quite some detail about how you use the tools we've just mentioned. You can also follow along with the photos we've included.

Apply flux to the pads of the components in question. It is a good idea to work in small groups of similar components. For example, you might plan to work with all the 10kΩ resistors.

If there are a small number of different values, then they can be worked in parallel. One exception to this are capacitors, which, as we noted earlier, do not usually have any distinguishing markings. In that case, we recommend sticking to a single value at a time.

Roughly place the components on their pads. Flux gel or paste will generally be sticky enough to hold them in place. You might find that your tweezers pick up small amounts of flux and will then stick to components. That's another reason to keep everything quite clean.

Adjust the component with the tweezers so that it is centred on its pads. The amount of PCB pad visible will dictate how easy it is to apply the soldering iron, so symmetrical placement is not just neat, but crucial to ease of soldering.

For tiny leads, it can help to apply some flux to the top of the lead too. Clean the iron's tip and apply a minuscule amount of fresh solder to it.

Gently hold the component down flat against the PCB with the tweezers and touch the iron to both the pad and lead together. Hold it there for a second to allow the parts to heat up and bond with the solder. You should see the solder flow from the iron and onto the part and pad.

Remove the iron and continue to hold the part in place while the solder solidifies. One second will be sufficient for small parts with fine leads, perhaps longer for larger components.

If the part has moved or is not flat against the PCB, grip it with tweezers and apply heat to melt the solder. Adjust its position until you are happy.

If the part looks like it is still well-aligned and flat against the PCB, apply some fresh solder to the iron and work through the remaining pads.

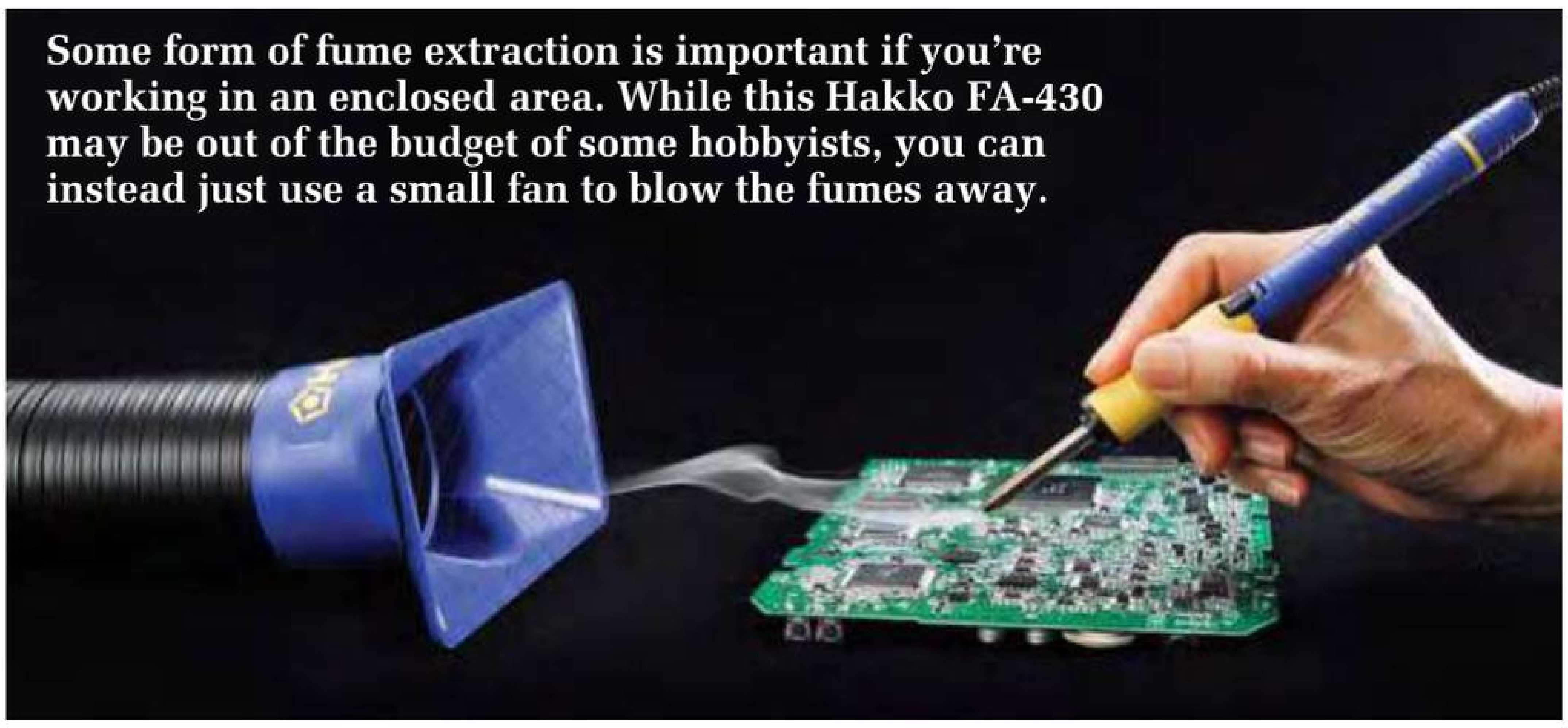
For very narrow or fine pads, place the iron onto the pads first. The solder mask on the PCB will help to prevent the solder from flowing where it shouldn't. We try to enlarge the pads in many of our SMD projects to make this easier, although you won't find this in all designs.

Depending on the iron, pad and flux, the solder may be drawn onto the pad and lead by surface tension alone. The advantage of this is that the iron does not obscure the view of the lead so that you can observe the joint forming. The behaviour of solder and its surface tension at the small scales used for SMDs is critical, so this will help you get a feel for what works.

You might have seen parts being soldered with solder paste in a reflow oven; when the solder liquefies, the part snaps into the correct location. This is due to the surface tension, pad location and the importance of the solder mask.

Surface tension also pulls solder exactly where it is needed. Only a tiny amount of solder is required if the parts are flat against the PCB. If you see clean, curved fillets of solder, that is a good indication that the joint is well-formed.

You can use surface tension to apply a generous amount of solder to ensure a strong joint. A bulging but clean and glossy joint is sure to be more functional and solid than a tiny fillet that cannot be seen, just as long as it doesn't bridge out against any other part!



Some form of fume extraction is important if you're working in an enclosed area. While this Hakko FA-430 may be out of the budget of some hobbyists, you can instead just use a small fan to blow the fumes away.

Table 2 – common types of solder

Type of Solder	Composition/Name	Melting-point	Comment
Lead-based	SnPb 60/40%	188°C	Higher tin (Sn) concentrations lead to greater strength
	SnPb 63/37%	183°C	Eutectic – melts/solidifies at a single temperature
Lead-free	Sn100C	227°C	Silver-free; contains copper, nickel and germanium
	SAC305	217-220°C	Contains tin, silver and copper; used in wave soldering
	SnCu	217-232°C	Contains tin and copper; tin-based lead-free solders are quite often used for reflow and wave soldering
	SAC387	217-219°C	Contains tin, silver and copper
Flux	Rosin	NA	Helps to facilitate soldering
	Non-rosin	NA	Often contains metal halides such as zinc chloride, hydrochloric acid or citric acid etc – can be corrosive
Hard solder	Silver, copper, brass, bronze	>450°C	Often used for jewelry and are designed to have a melting point just below that of the corresponding metal

These movements are what has to be practised. The timing will also depend on things like your iron temperature and choice of (tin-lead or lead-free) solder.

If you experience a solder bridge, and as long as the part is correctly aligned, continue to solder the remaining leads. Then sort out the bridge.

Use the technique described earlier to remove solder from bridged leads. Apply more solder if needed (especially if you can't easily access the bridge). Apply flux, braid (see below) and then the iron. Allow the braid to absorb some solder, then carefully slide both away.

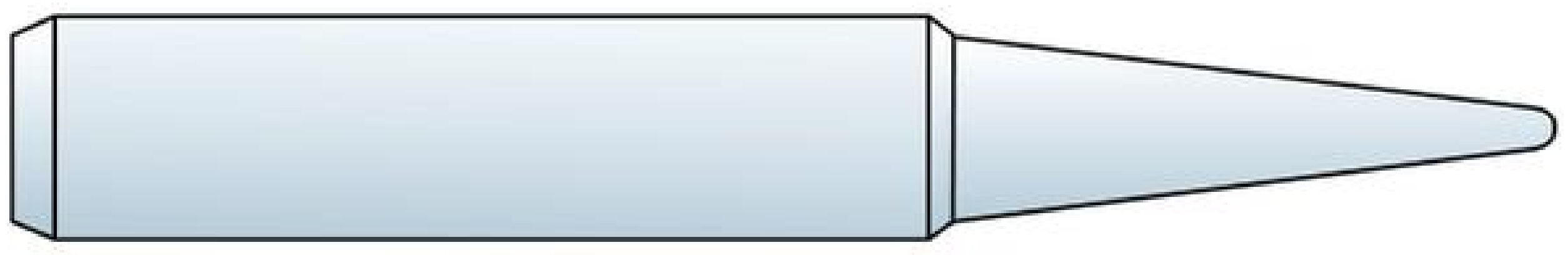
Inspect the part closely with a magnifier. If the joint appears dry or unclean, then apply fresh flux and gently touch the clean iron tip against each lead in turn. You'll find that even this step of refreshing each lead will help distribute solder to where it should be.

Drag soldering

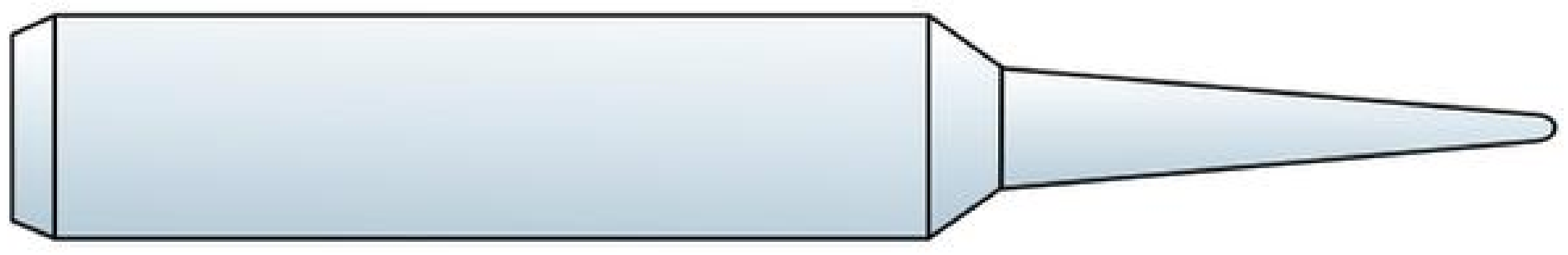
When SMD components have pins that are very close together, it becomes impractical to solder them individually. The only component on the *SMD Trainer* PCB that we would consider having such tight pin spacings is IC2, in an SSOP package with 0.65mm pin pitch. Some chips have an even finer pitch, down to about 0.4mm (eg, TQFP-144).

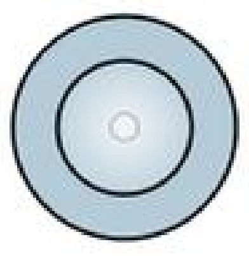
In these cases, it's easier to drag solder the ICs. Once the chip has been tacked in place and flux applied to the pins, a small amount of solder is loaded into the iron's tip and then gently dragged along a row of pins. Surface tension pulls a small amount of solder from the tip and onto the pins. Done correctly, it forms perfect joints the first time.

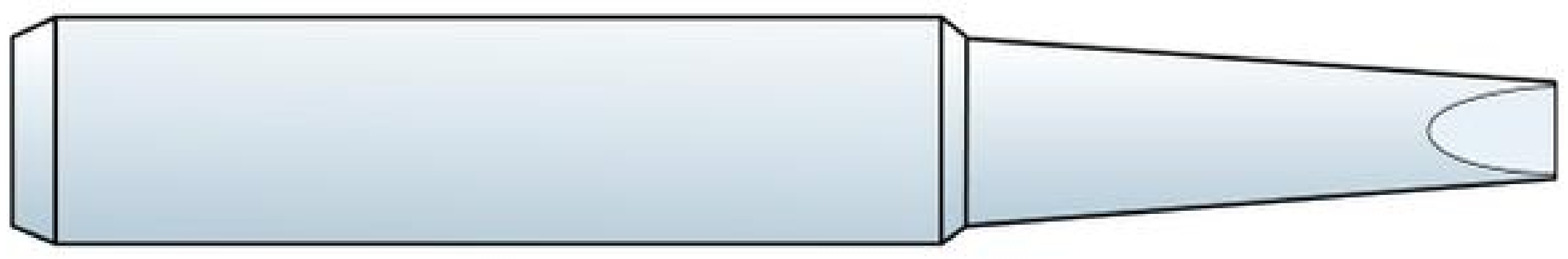
It's generally better to apply too much solder than not enough because bridges are easier to see than joints with insufficient solder, and they are easily cleaned up using braid (see below) and more flux.


Pointed or Conical (Medium)

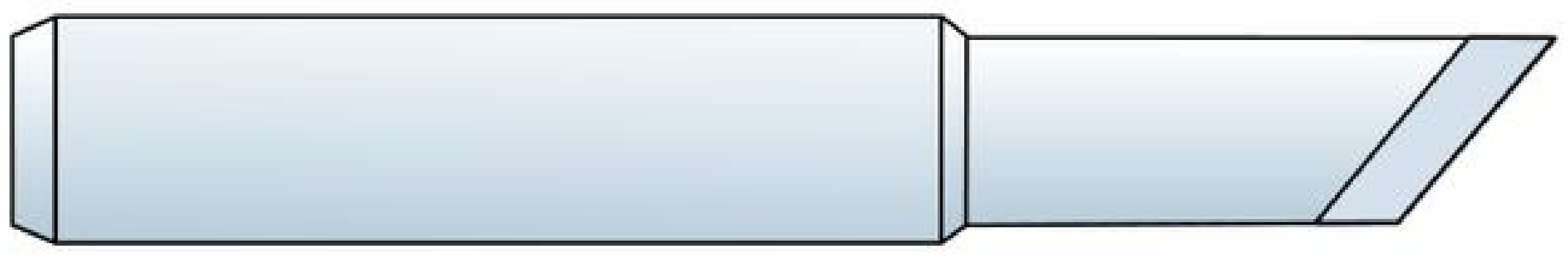
Medium conical tips are used for general soldering including through-hole and larger SMD components. They have the advantage of being usable at virtually any angle.


Pointed or Conical (Small)

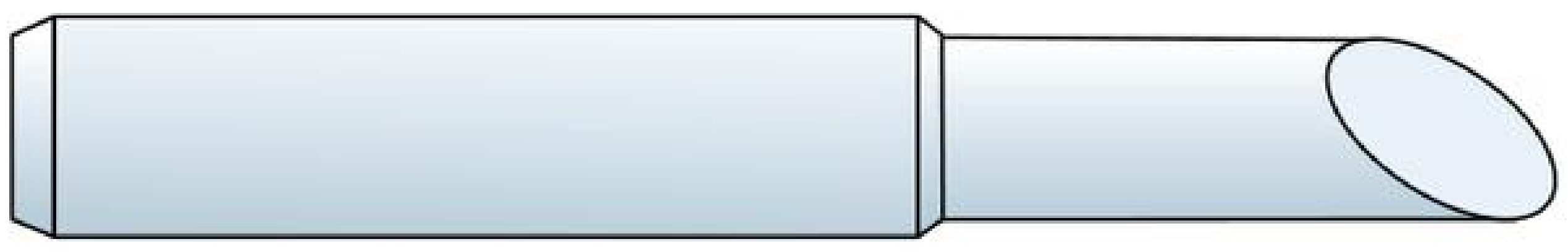

Finer conical tips are able to make contact with smaller leads, so they are more suitable for soldering large-to-medium SMDs, while still working with smaller through-hole parts.


Screwdriver or Chisel

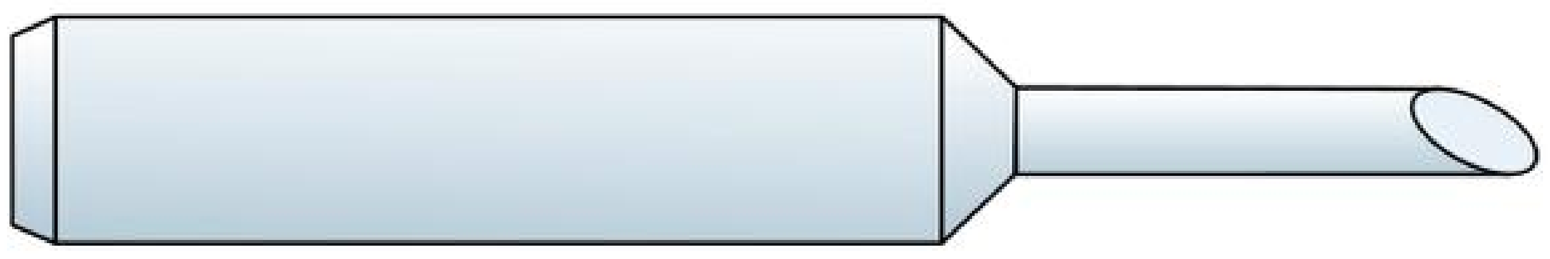
The wide contact area of chisel tips makes them handy for applying solder wick to remove solder, as well as heating SMD tabs or reflowing the pins on one side of a device.

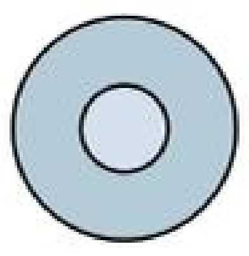

Blade or Knife for soldering SOIC & PLCC SMDs

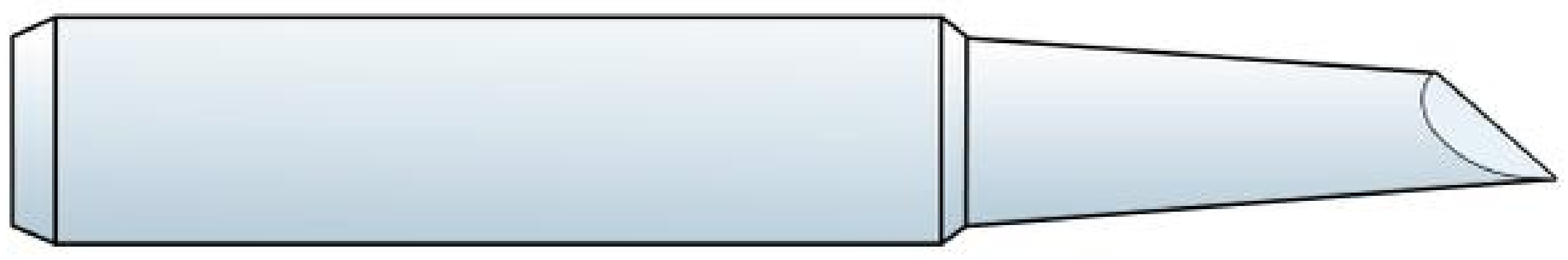
Like the chisel, the knife tip can make contact with a large area of the board at one time. Its angle makes it more comfortable for running down the sides of ICs.


Large bevel tip

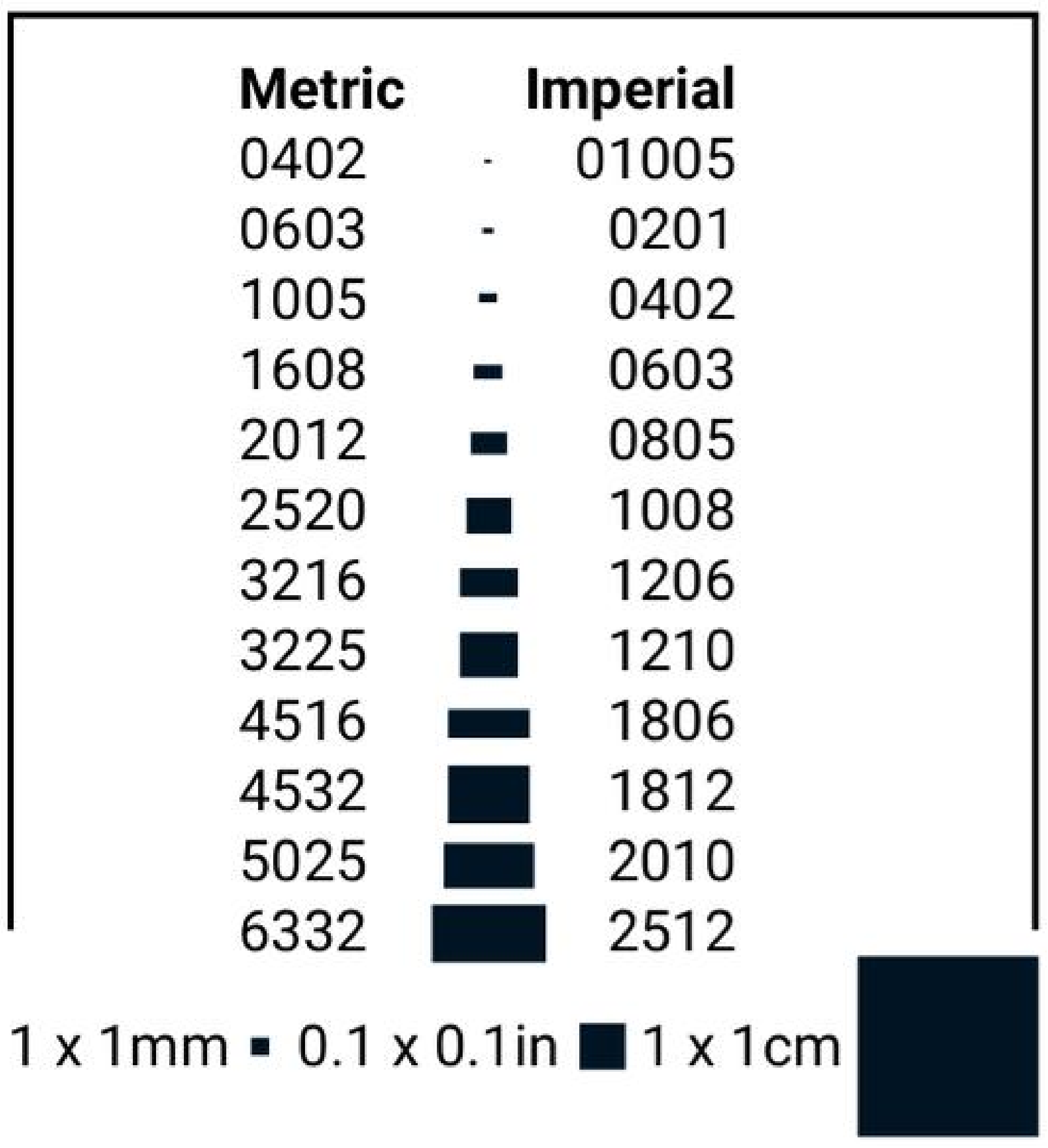
Bevel tips can contact an even larger area but the larger tips like this one are generally too large to get near smaller components.


Small bevel tip


Smaller bevel tips are not only more manoeuverable but you can also angle them to make contact on just one edge, or the whole face when needed.


SMD 'Flow' tip

An SMD flow tip is similar to a bevel tip but it has a depression in which to hold molten solder. This makes them ideal for drag soldering many pins at once.



Metric	Imperial
0402	01005
0603	0201
1005	0402
1608	0603
2012	0805
2520	1008
3216	1206
3225	1210
4516	1806
4532	1812
5025	2010
6332	2512

1 x 1mm ▪ 0.1 x 0.1in ■ 1 x 1cm

This diagram shows common SMD component sizes at actual size. The metric 0402 component is so small that it is barely visible!

You can get special flow soldering iron tips with 'wells' (depressions) to hold the solder for this technique, but you can get away with a standard tip. You just have to add more solder to it more often (eg, every 5-10 pins soldered instead of every 30-40 pins).

Even larger-pitch ICs like the SOIC types can be soldered using this sort of technique; it can be quicker (and neater) than soldering them individually.

Using braid

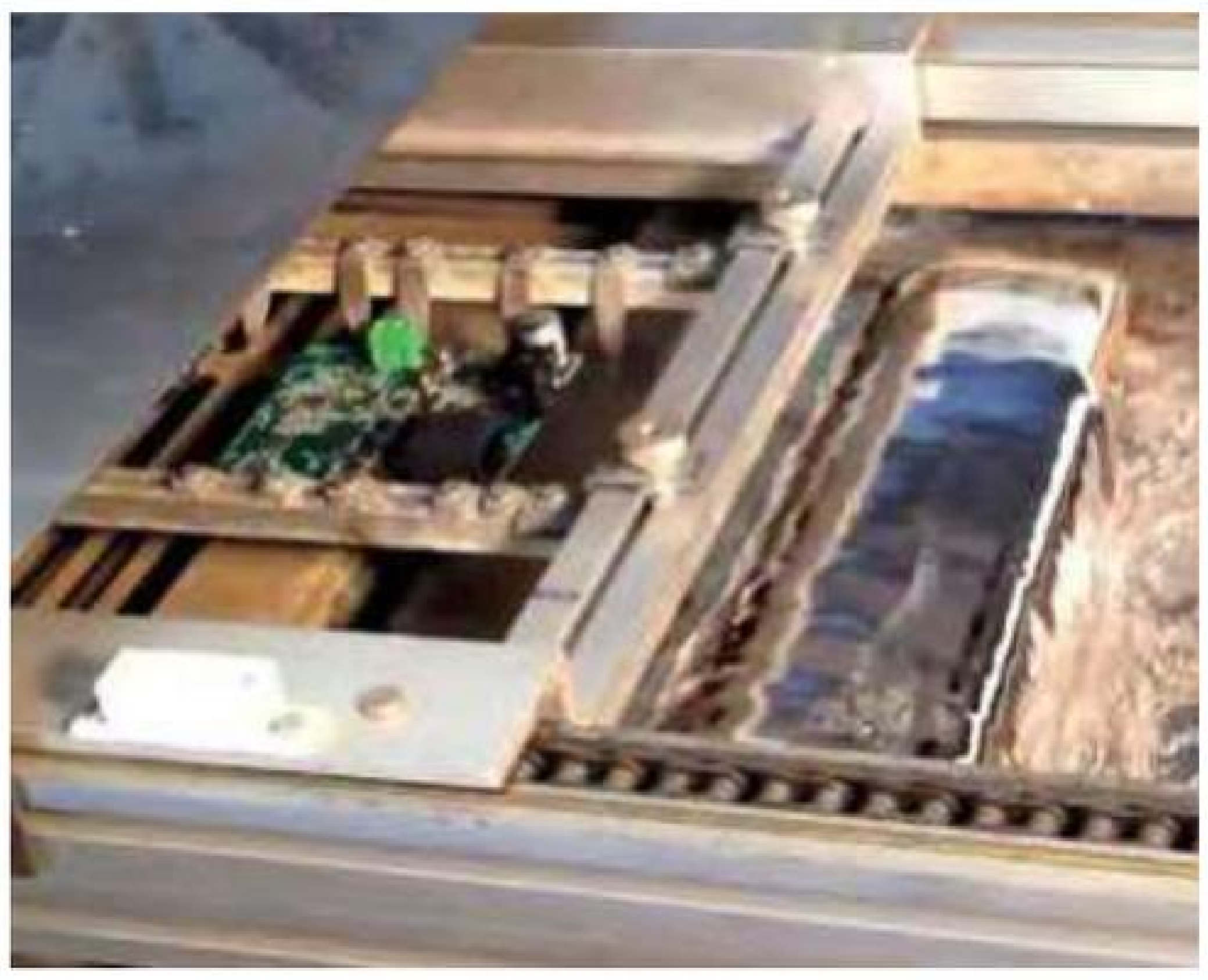
Solder braid is best for removing small amounts of solder, while a solder sucker is better for removing large volumes. So if you have a lot of solder to remove, start with the sucker to remove the bulk and finish with the braid to tidy up.

But at the tiny scales involved with SMD parts, solder suckers become unwieldy and likely to simply inhale your parts as well as the solder you're trying to remove. The amounts of solder you need to remove will be pretty small too.

Before using the braid, it helps to add flux. The word 'flux' comes from the Latin word 'fluere', meaning to flow; we want to encourage the solder to flow into the braid.

Press a clean part of the braid onto the solder with your iron and allow everything to heat up enough to melt the solder; it should start to soak into the braid. Being made of copper, the braid conducts heat well, so place your grip with care or use tweezers.

After the braid takes up the solder, carefully move both the iron and braid together by sliding away across the PCB. You don't want to remove the iron first and have the braid soldered to your PCB!



An example of wave soldering showing the PCB leaving the heater portion of the machine and being moved to the solder wave.
Source: https://youtu.be/VWH58QrprVc

It can sometimes help to add more solder where you want to remove it, especially if it's a solder bridge tucked deep between two pins. The extra volume can give the braid more surface to contact.

If there is a dark residue on your PCB after using braid, this is probably the byproduct of the flux working. For areas like this, a cotton-tipped swab dipped in flux cleaning solvent can be used to clean small regions before continuing.

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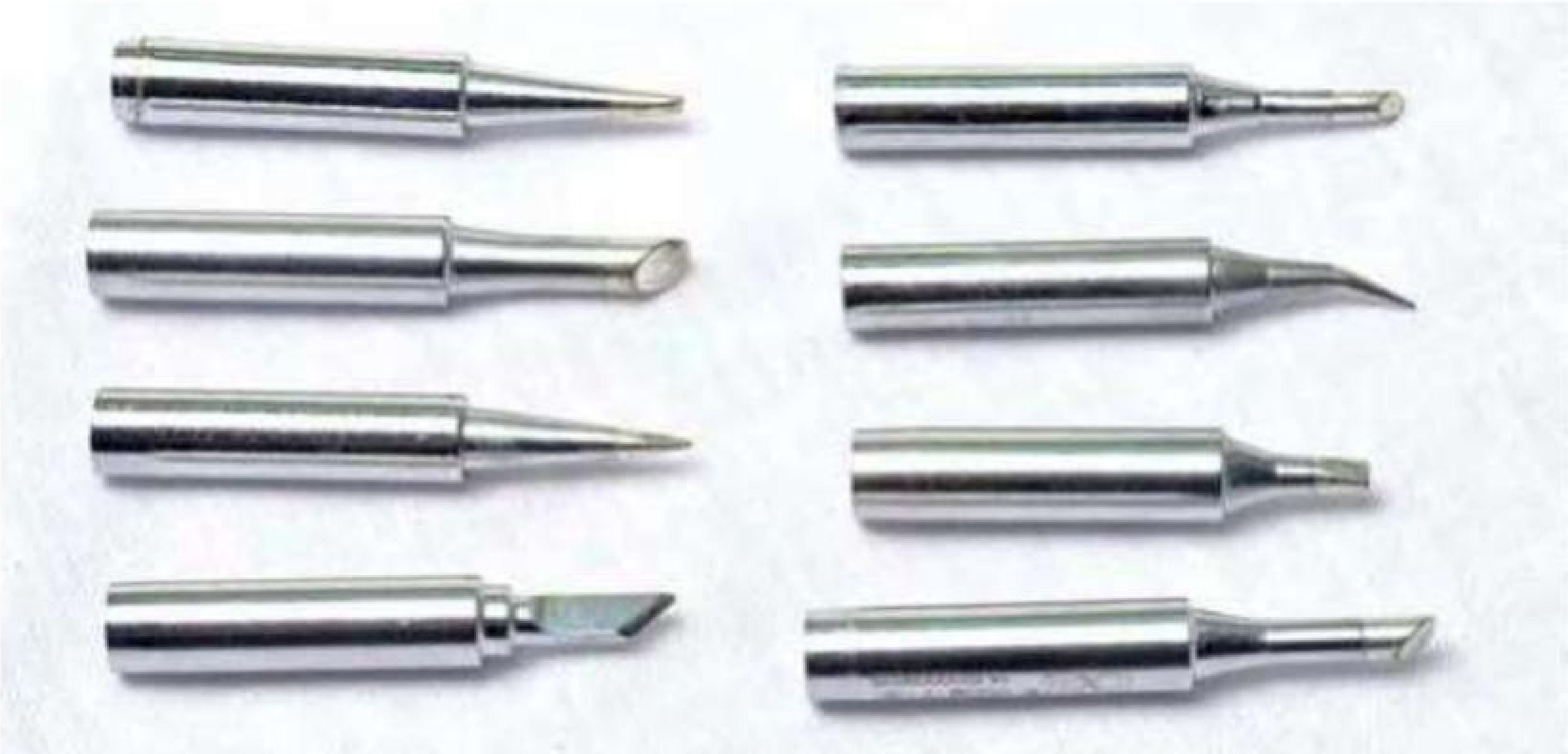
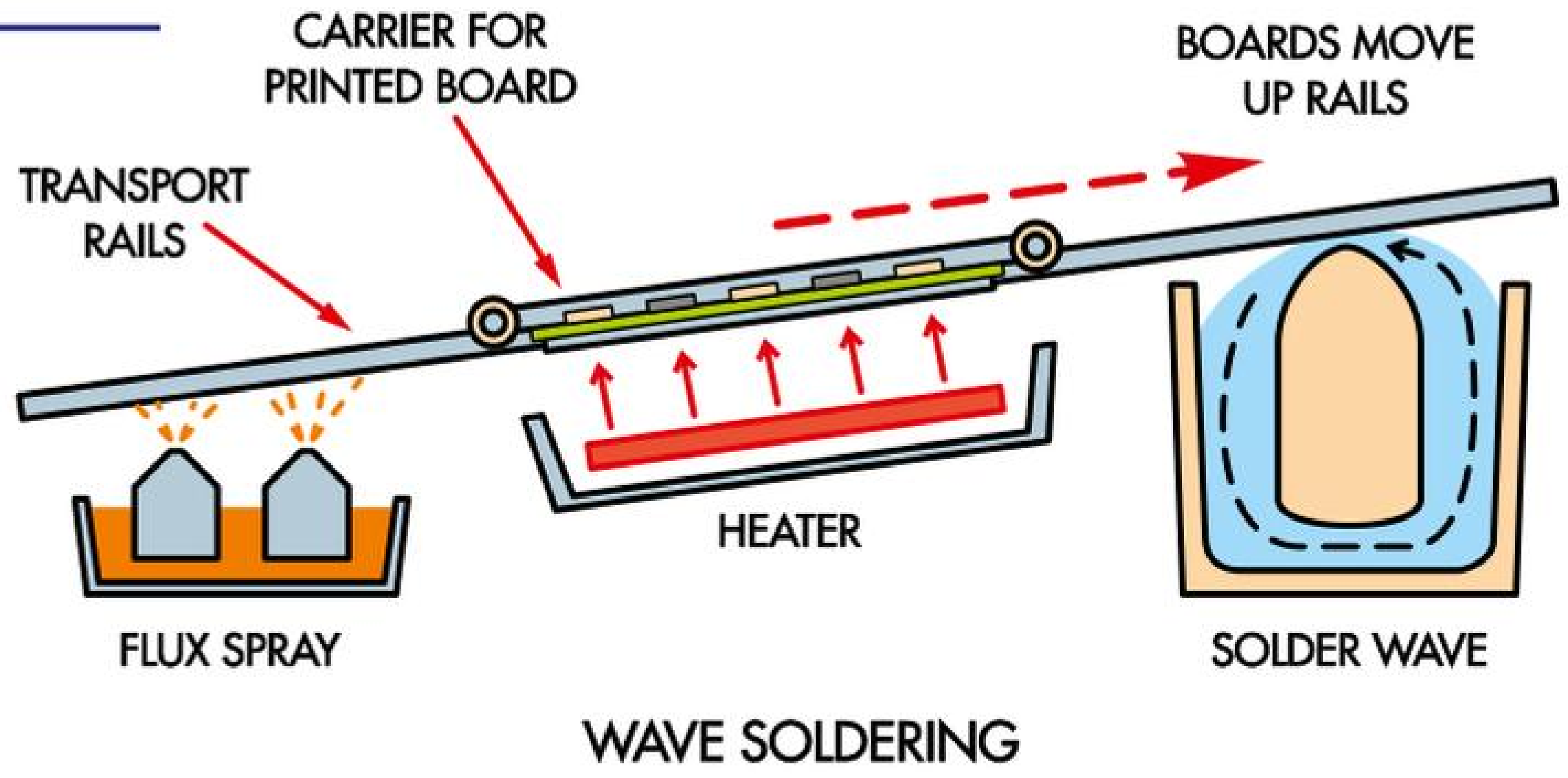


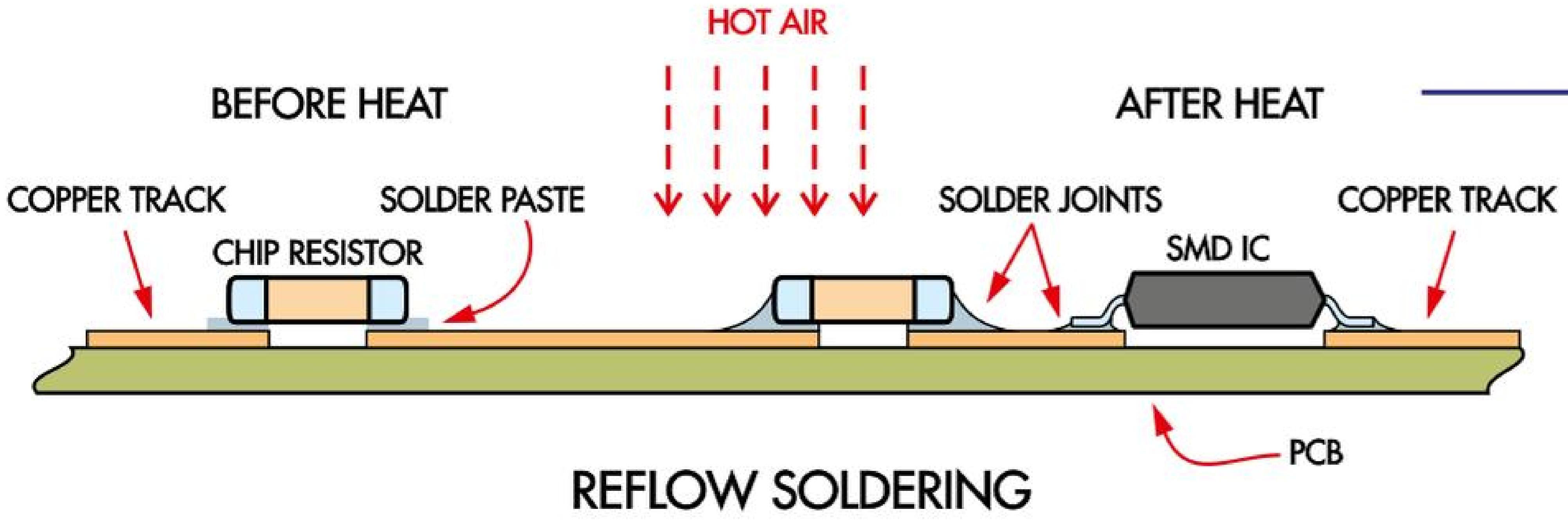
Common soldering iron tips; most are suitable for SMD work.

When drag soldering you'll typically use a flow or bevel tip. The easiest way to learn hown to drag solder is to watch a video, such as the many found on YouTube; for example: https://bit.ly/pe-dec22-drag

AMI
9552YFS
6703-004
UDS
L42000650

The basic principles of wave soldering. The PCB is carried along over the solder bath by a conveyor. At one point, the solder is forced up in a 'wave' so that the bottom of the board passes through it. The components and copper tracks are soldered and the board then emerges from the bath. ►





◄ **Reflow soldering doesn't use a soldering iron at all – temperature-controlled hot air or IR is used to melt the solder 'paste' applied to the component and copper tracks to be soldered. The board passes through the oven, the solder paste melts and – hey presto! – a soldered joint.**

AUDIO OUT

By Jake Rothman

Universal single op amp board (optimised for audio electronics) – Part 1

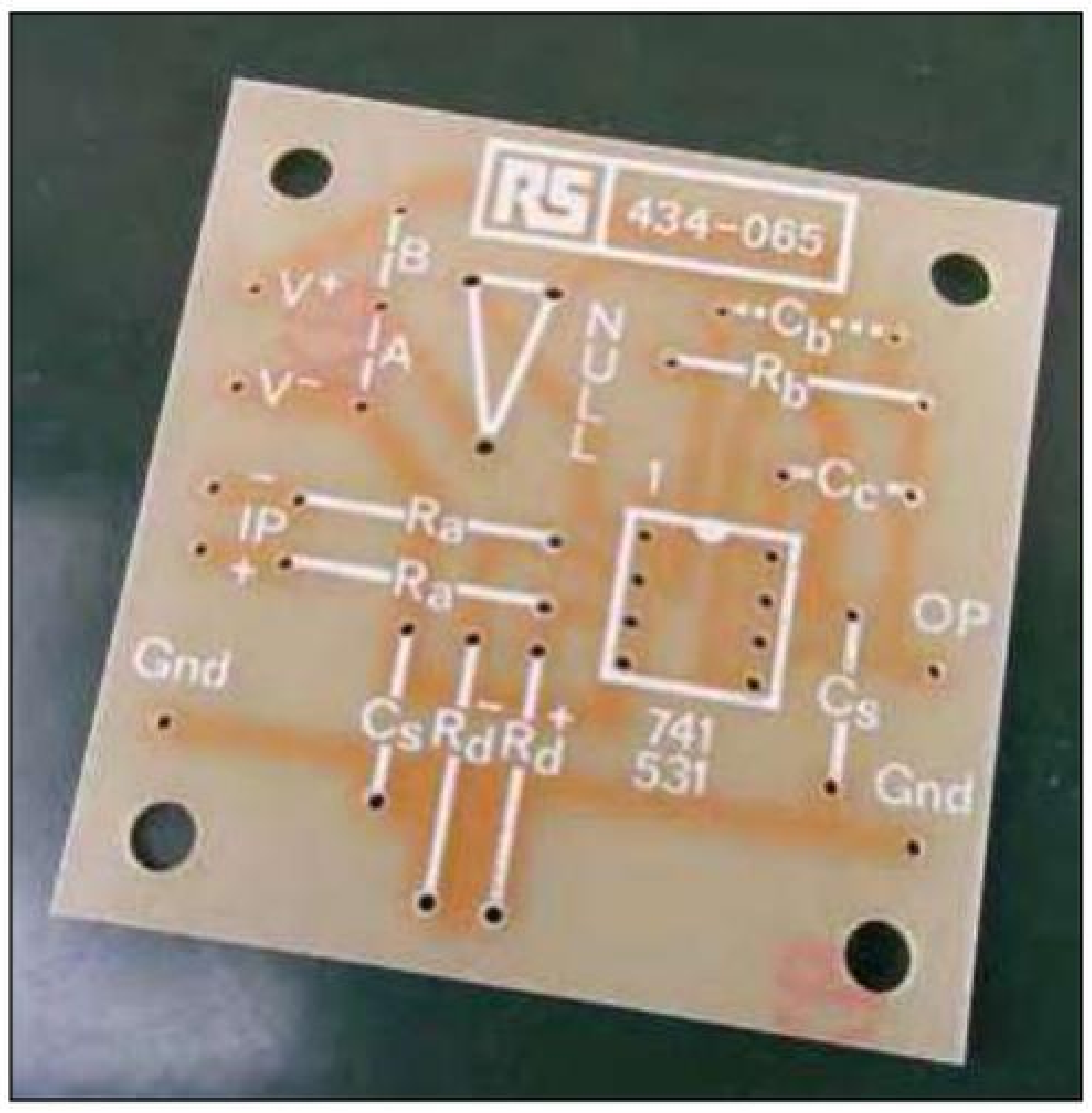


Fig.1. The discontinued RS op amp PCB. Now we have a better replacement, optimised for audio, but perfectly useable for general op amp applications.

Often the subject of this column is initiated by a reader's request. In this case, Mr Martin van Doorn from Holland needed an op amp tester. To create a tester that covered every op amp parameter would be very complex – more a job for a team at say Peak Electronic Design than my own 'sole-trader' approach. So, having dodged that job, I did come up with a viable alternative idea.

Mission creep

In audio equipment, op amps are surprisingly reliable, with a failure rate almost as good as single small-signal transistors. Their most common failure mode is the inputs getting zapped by abuse – for example, connecting large, charged capacitors or 48V phantom power with no protection. This usually results in the output permanently stuck at one of the power rails or a short between the power pins. In such cases it's a straightforward go/no-go test with a DVM/multimeter or simply sniffing for smoke. A more subtle failure is input transistor degradation, resulting in a high noise level, a major problem for audio work. The best way to test this is to put the offending op amp into a high-gain amplifier and have a listen if you have good ears, or check with a 'scope if – like me – your hearing is no longer top notch. In the end, I decided that to test op amps the best I could to do was to design a universal circuit board where most of the standard op amp configurations could be easily built.

Getting board

RS used to sell a generic op amp board, as shown in Fig.1. Maplin also did one. I've used lots of the now discontinued RS boards over the years, such as in the *EPE Test Amplifier* and the *Upwards Compressor* shown in Fig.2. Since such a useful board is no longer available, it's obviously time to produce a *PE* replacement, and while we're at it,

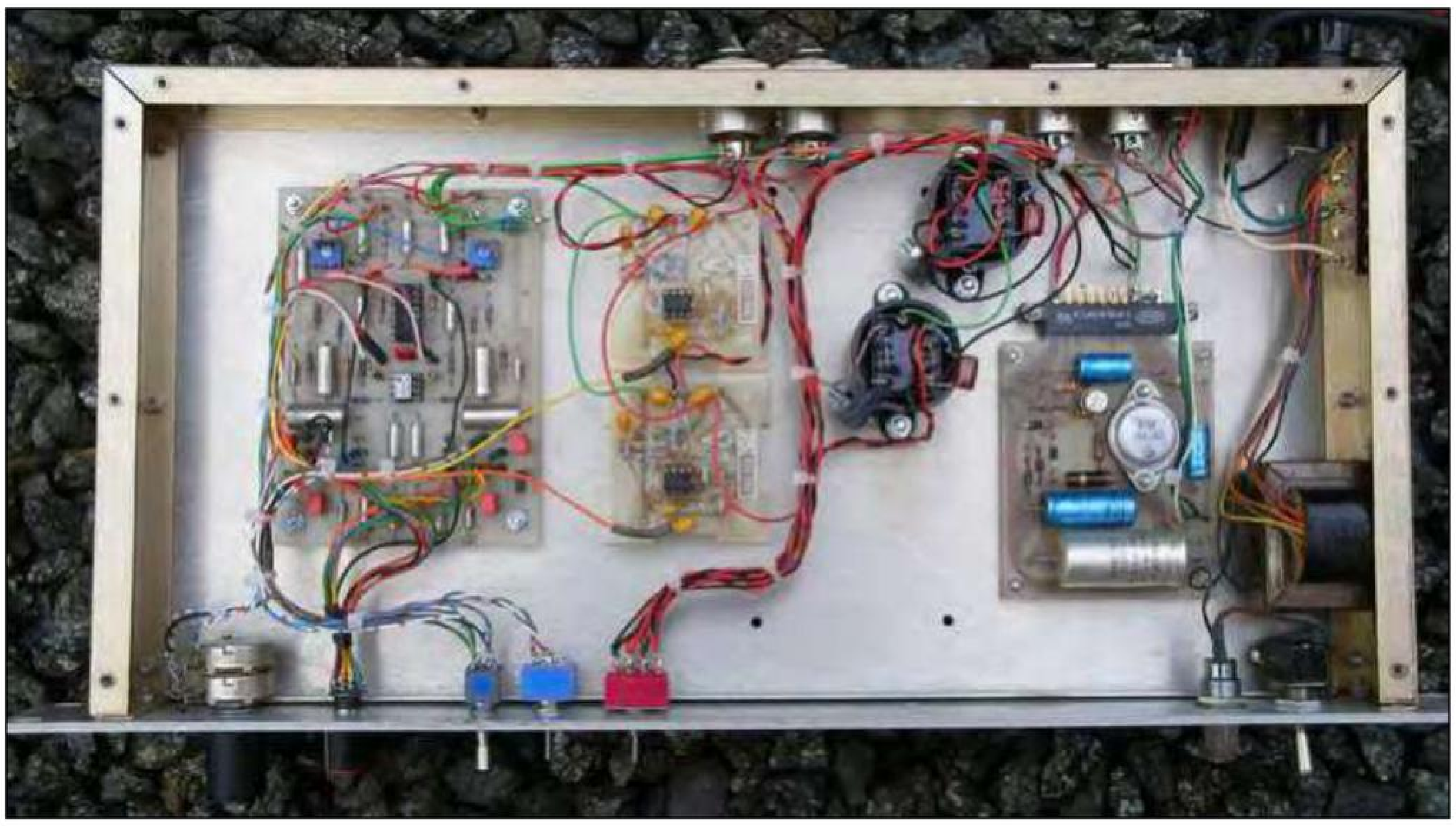


Fig.2. Here's a typical studio application for the RS boards, adding balanced XLR inputs to an upwards compressor (low-level ambience booster).

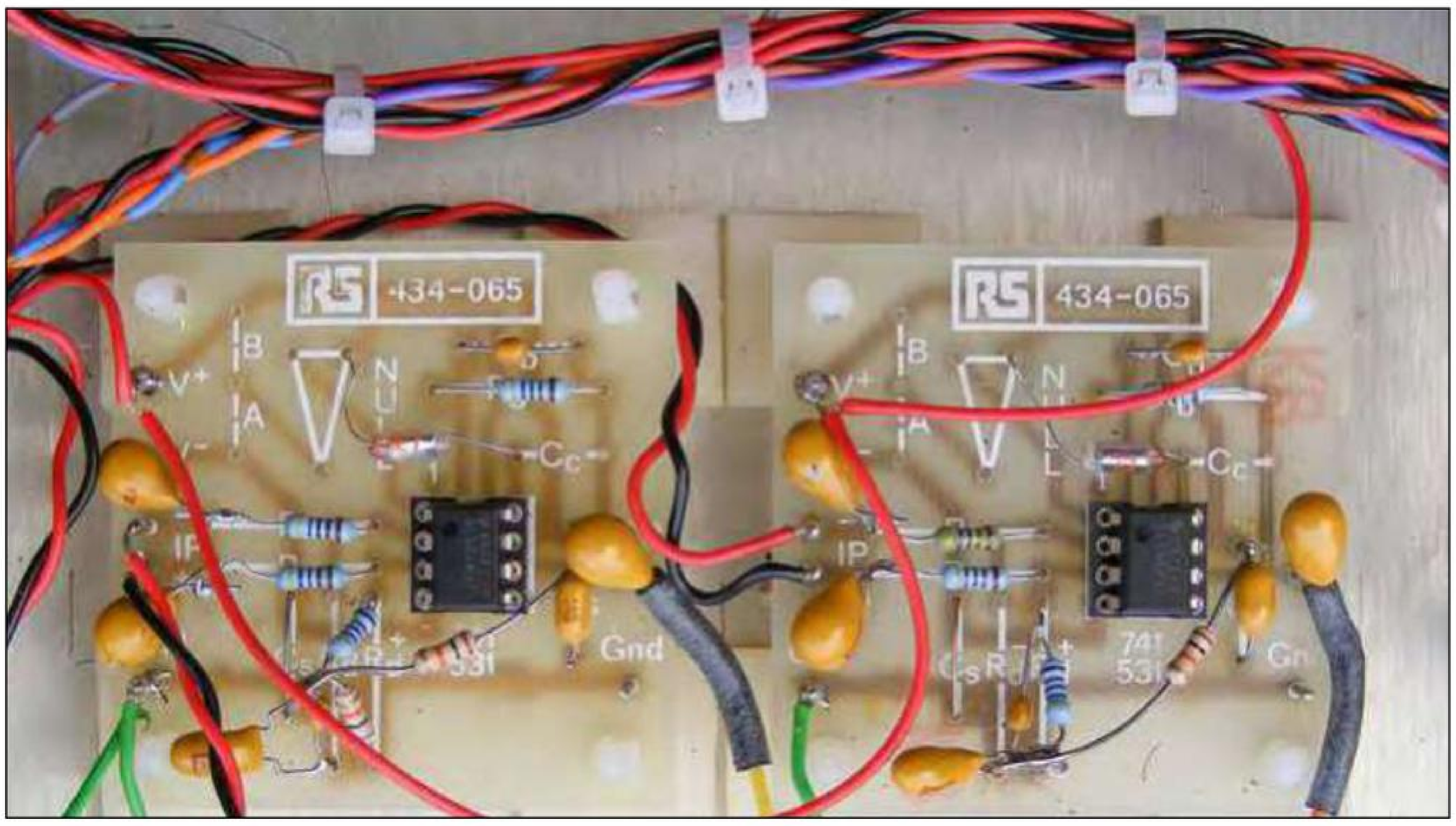


Fig.3. A problem with the RS board was a lack of provision for the large capacitors required for audio work.

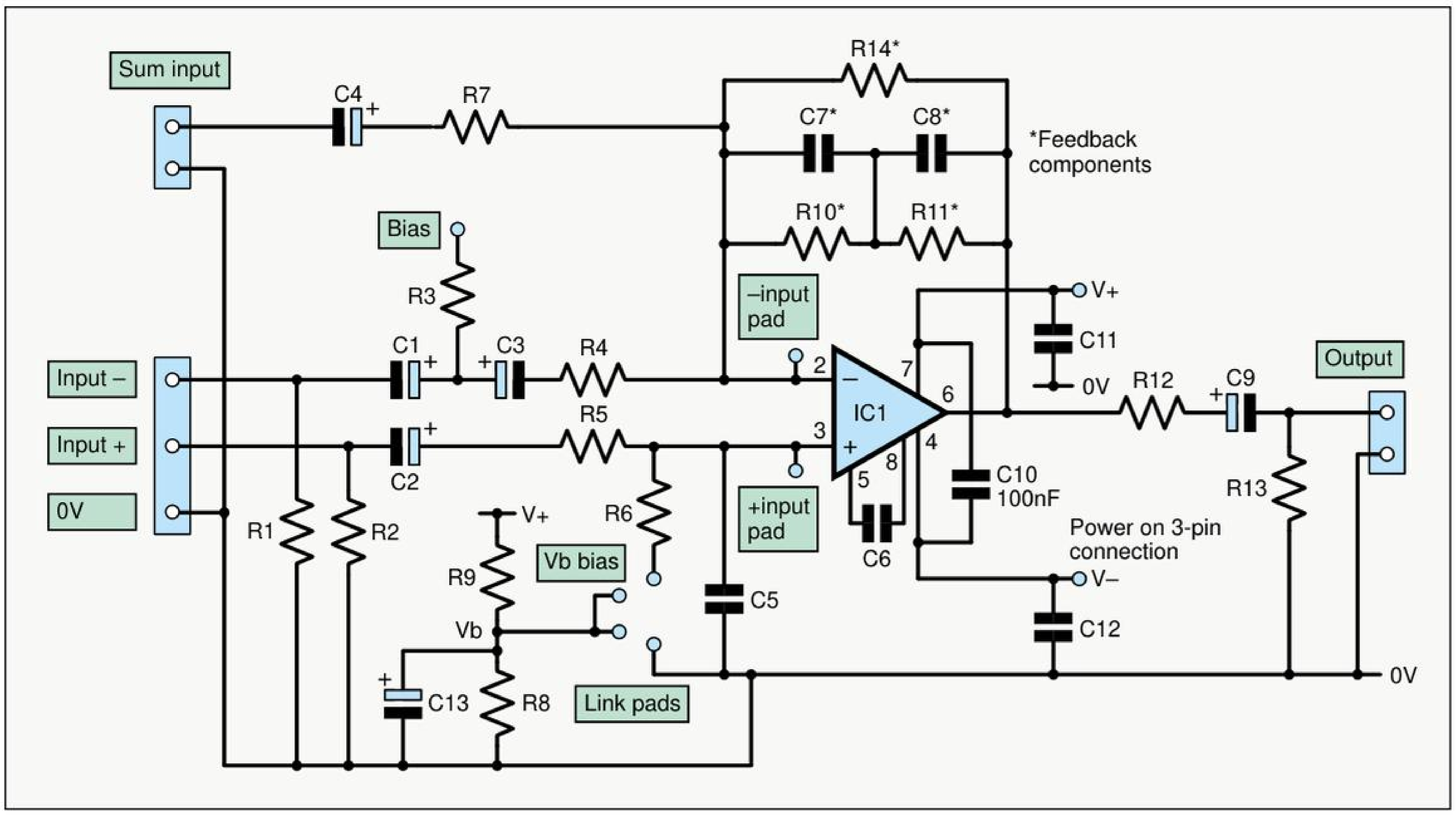

Sum input
C4
R7
R14*
C7*
C8*
*Feedback components
R10*
R11*
Bias
R3
–input pad
V+
C11
0V
C1
C3
R4
Input –
2
7
6
R12
C9
Output
Input +
R5
3
IC1
4
8
5
C10 100nF
R13
0V
R1
R2
C2
V+
R6
+input pad
C6
Power on 3-pin connection
V–
R9
Vb bias
C5
Vb
C12
C13
R8
Link pads
0V

Fig.4. The general circuit diagram of the universal op amp board. Not all the components are used at once, only a selected few for a specific circuit.

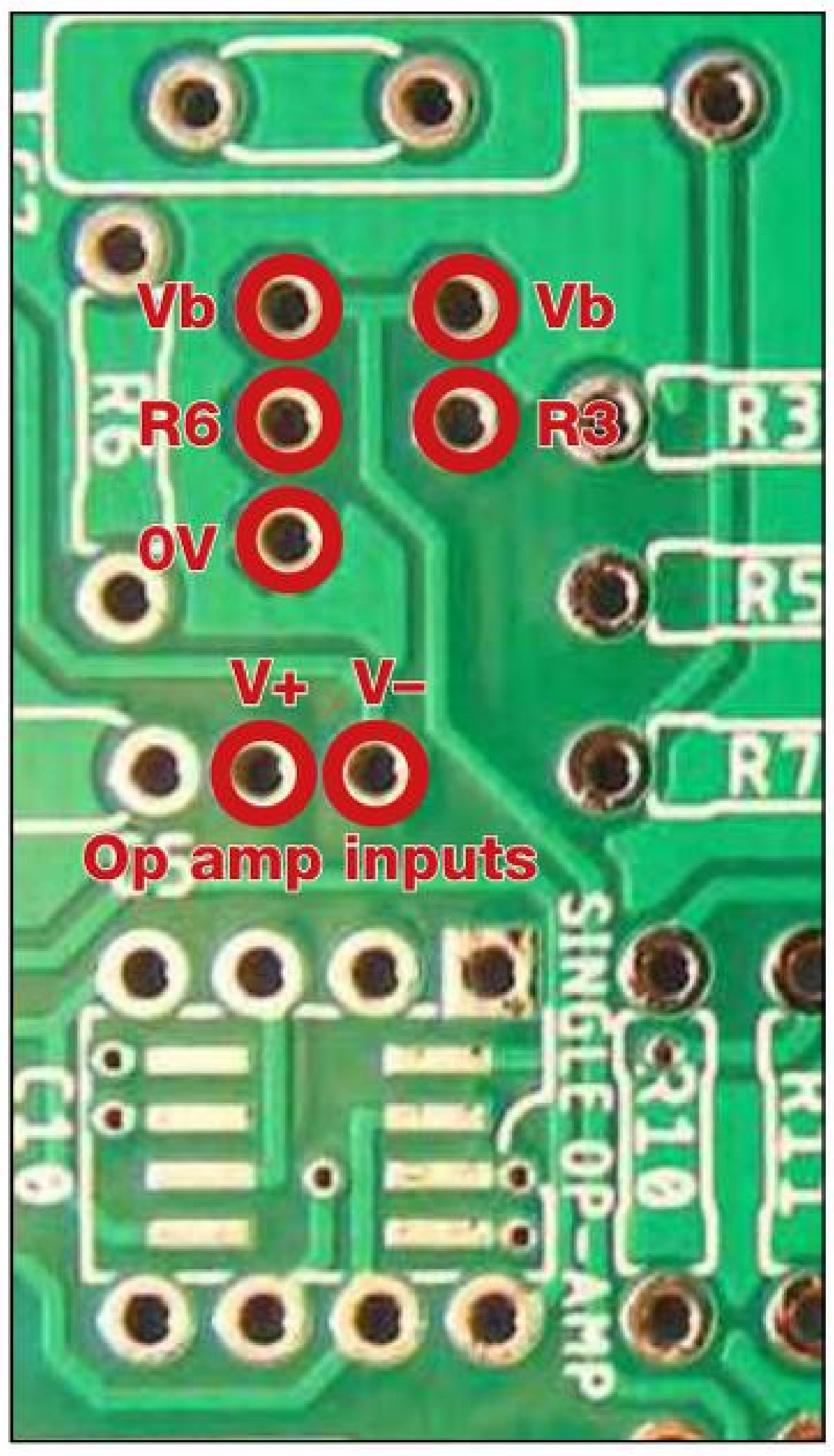

Vb
Vb
R6
R3
0V
V+
V–
Op amp inputs

Fig.7. There are links provided for bias and grounding. Note the PE boards have an extra grounding pad. There are also connection points going to input pins 2 and 3 on the op amp near C5. These are useful when pots have to be connected for gain control. There is also a link to R3 for biasing bipolar capacitors made up of C1 and C3. Finally, there are three ground pads – see Fig.5.

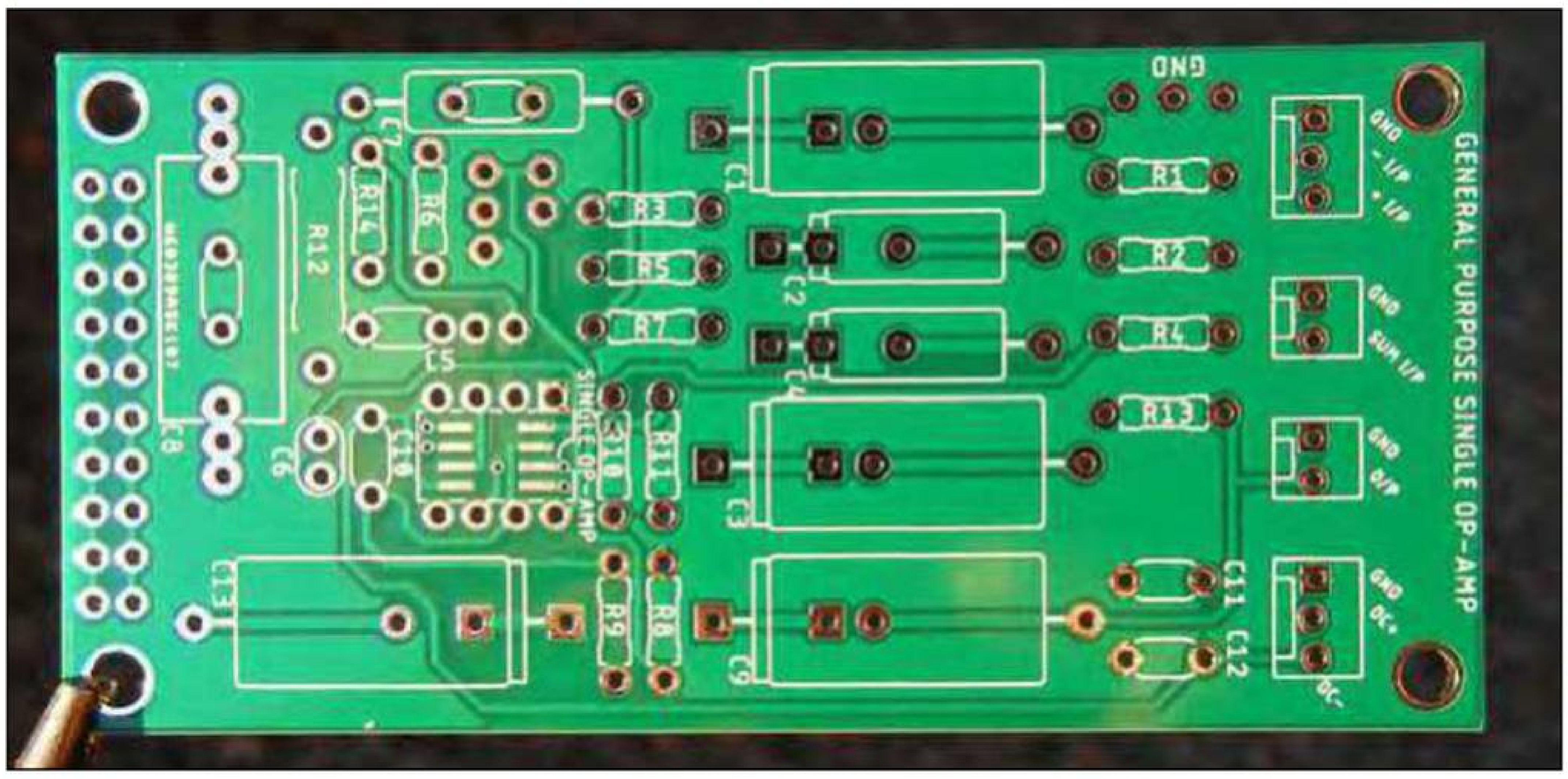

GENERAL PURPOSE SINGLE OP-AMP
GND
R1
R2
R3
R4
R5
R6
R7
R9
R8
R10
R11
R12
R13
R14
C1
C2
C3
C5
C6
C7
C9
C10
C11
C12
C13
SUM I/P
O/P
DC+

Fig.5. The overlay of the general op amp board.

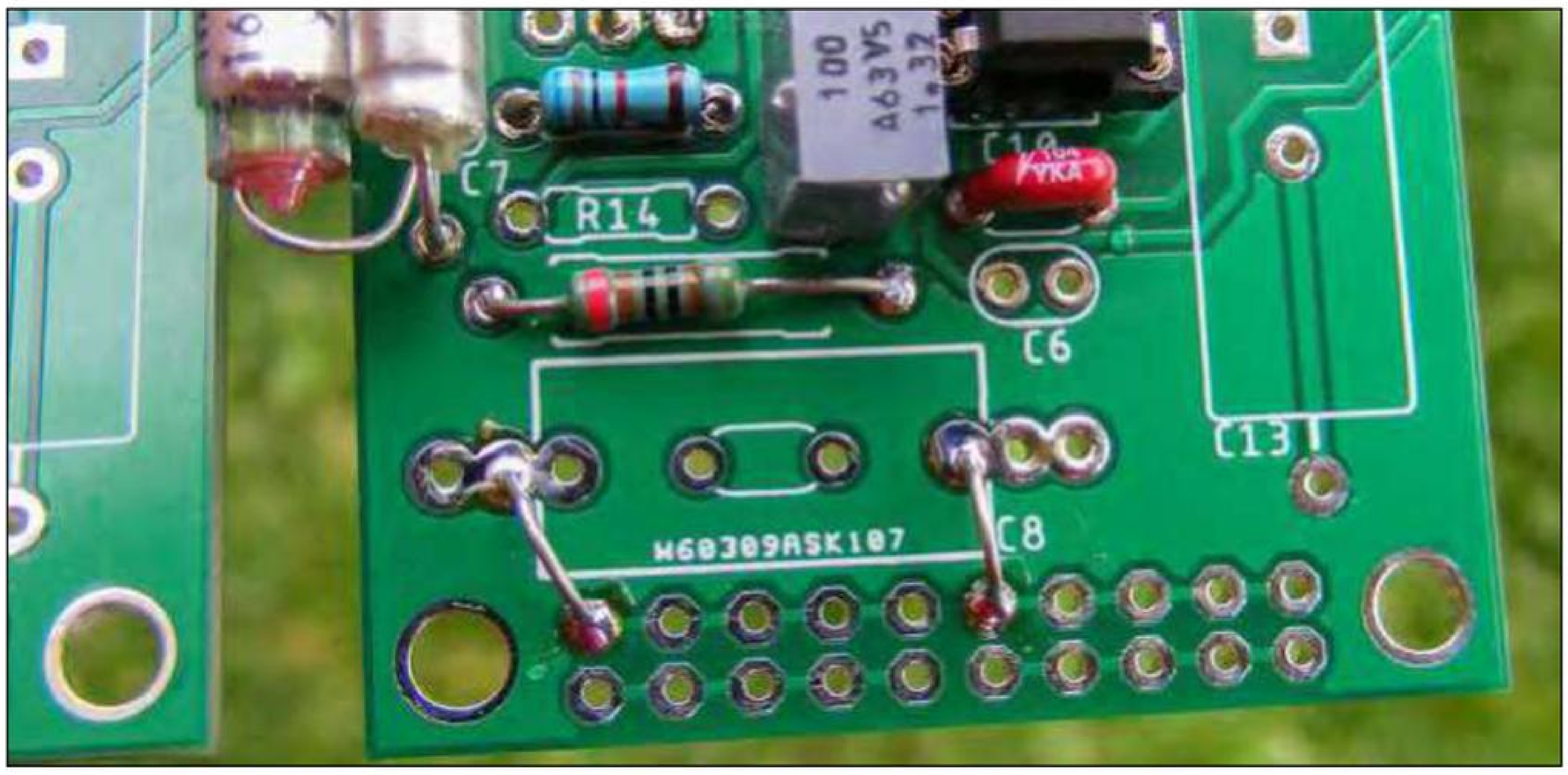

C7
R14
C10
C6
C13
C8
W60309ASK107

Fig.6. The board has provision for experimentation in the form of four 'blob points'. Essentially, five pads connected in strips like a bread board.

upgrade the late-1970s single-sided unplated-through-hole implementation.

The RS boards were designed for DC instrumentation use, reflecting RS's mainly industrial clientele. When I used them for audio applications there were often large capacitors hanging off precariously, as shown in Fig.3. So, accommodation for these larger components was necessary in my new design. On the other hand, some instrumentation requirements, such as the large off-set adjust preset, could be omitted. Also needed was a half-rail bias network for single-rail operation. Plus, one of the most popular audio op amps, the NE5534, sometimes requires a compensation capacitor across pins 5 and 8.

Chip multipacks

Some of the best audio op amps, such as the LM4562, are only available as dual devices. Generally dual devices are cheaper than singles, so we'll be needing a dual-channel board as well, a design which will be coming later. Quad op amps, such as the TL074, are rarely used

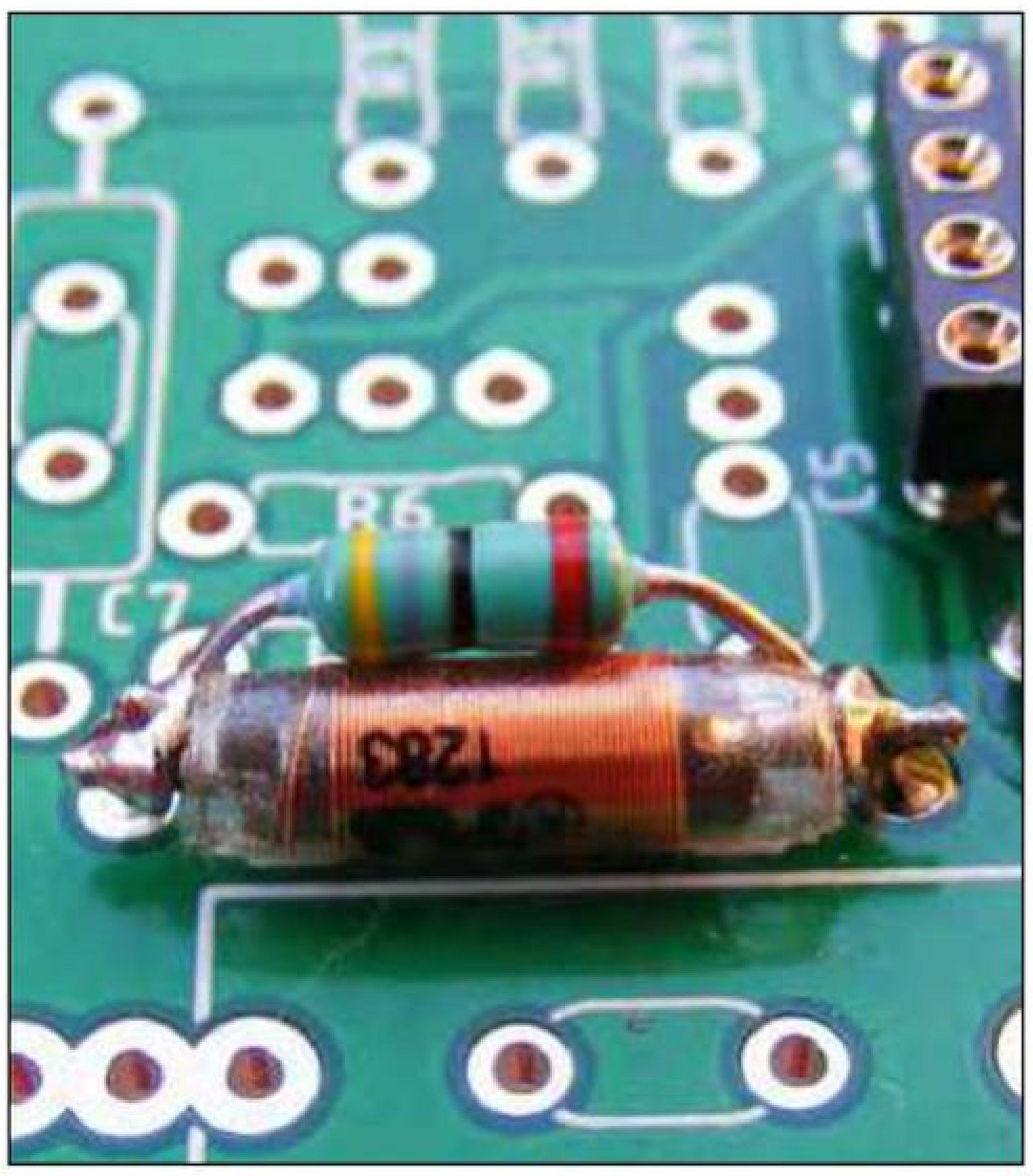


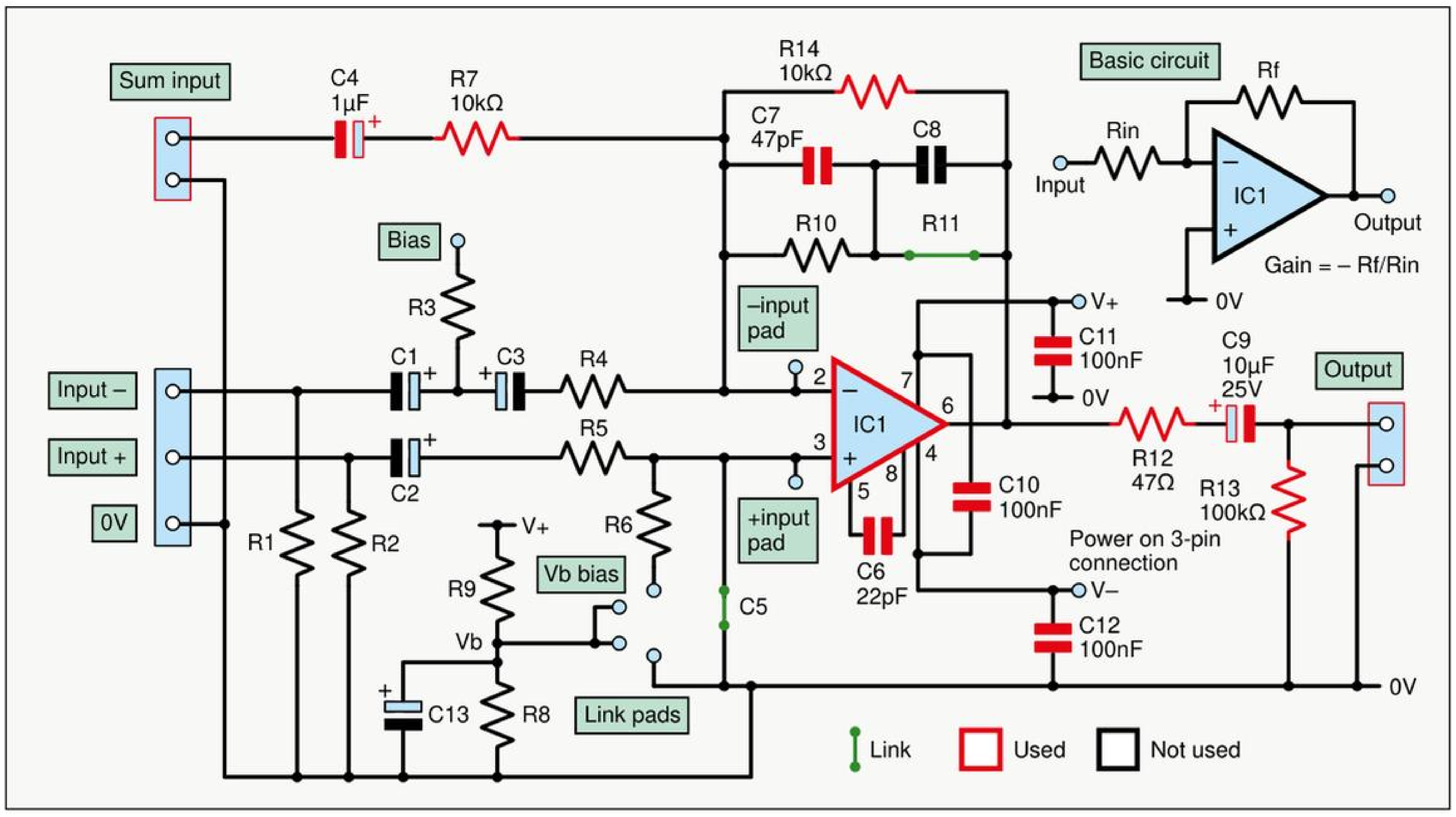
Fig.8. The output resistor outline is extra-large to allow a capacitive load isolator inductor network to be added.

for audio since it's difficult to get large audio capacitors to fit around them on the PCB. Apart from the LM837, there are very few low-noise quad devices for audio anyway, so we won't be bothering with quads. I do think a plug-in dual-to-quad adapter board is a good idea though. I would love to replace some noisy quads with a couple of NE5532s in some of my vintage gear. Has anyone designed one? If there is enough demand, I'll do a 2x 8-pin dual to 14-pin quad converter PCB.

Well-padded board design

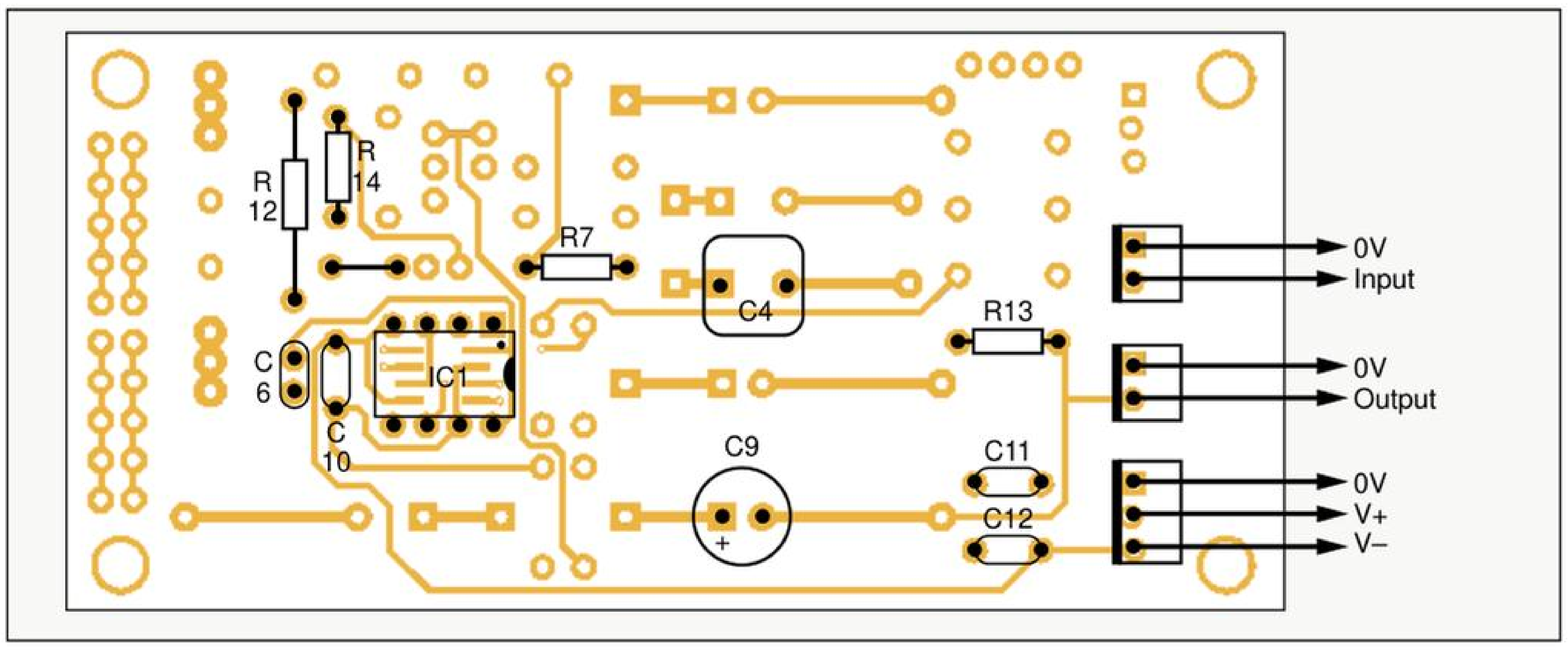
The overall schematic for the board is shown in Fig.4. It is optimised for audio applications, but is certainly not limited to audio. For any given circuit only some of the components will be inserted. The overlay with all the possible components is shown in Fig.5.

All the big capacitor positions have extra pads for different outlines. These allow radial or axial components to be used, and capacitors wired in parallel. There are also four interconnected pad groups or 'blob-points' for adding extra components for experiments on the left-hand side of the board. (Note how the blob points have been used to make it easy to add extra capacitors to make a parallel C8, as shown in Fig.6.)



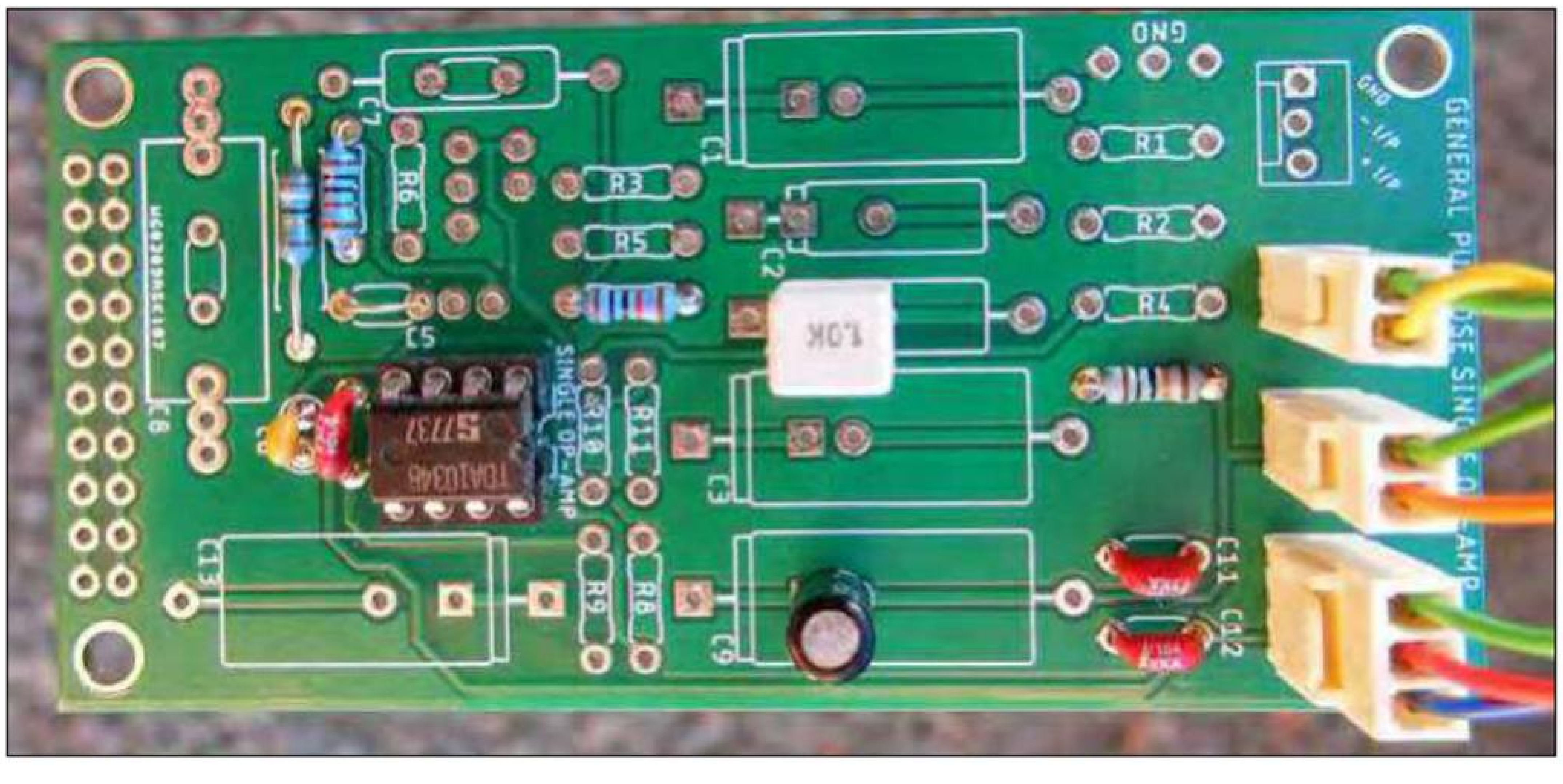
Sum input
C4
1µF
R7
10kΩ
R14
10kΩ
C7
47pF
C8
Basic circuit
Rf
Rin
Input
IC1
Output
Gain = – Rf/Rin
0V
Bias
R10
R11
R3
–input pad
V+
C11
100nF
0V
C9
10µF
25V
Output
Input –
Input +
0V
C1
C3
R4
R5
C2
IC1
R12
47Ω
R13
100kΩ
C10
100nF
R1
R2
R6
V+
+input pad
Vb bias
C6
22pF
Power on 3-pin connection
V–
C12
100nF
R9
Vb
C5
C13
R8
Link pads
Link
Used
Not used
0V

Fig.9. Inverting amplifier, a standard op amp configuration.



R12
R14
R7
C4
R13
C6
IC1
C10
C9
C11
C12
0V
Input
0V
Output
0V
V+
V–

Fig.10. Component placement for the inverting amplifier.



GND
R1
R2
R3
R4
R5
R6
C1
C2
C3
C5
C7
C9
C11
C12
C13
R8
R9
R11
10K
GENERAL PURPOSE SINGLE OP-AMP
TDA1034B

Fig.11. The assembled board – the op amp is a TDA1034, the original NE5534, designed by Philips. The date code is 1977 and this one was used in Pink Floyd's touring mixing desk made by Midas for Britannia Row. It's still working fine, having been installed many times.

Component functions

Normally, for a board like this, the components would be annotated according to their function. On the RS board for example, the negative feedback resistor was called Rb. To keep things simple for the PCB designer and constructor I've decided to stick with conventional numbering.

Here's a list of the components and their possible functions. Things will become clearer when specific circuits are shown where many of the board's component positions are left empty.

R1, R2 and R13

These resistors are an important audio addition. They are pull-down resistors which prevent clicks when input and outputs are connected. They hold the outputs of the coupling capacitors to 0V. Typical values would be a few tens of kΩ when using electrolytic coupling capacitors and around a few hundred kΩ for film and tantalum types (because of their lower leakage).

C1, C2 and C3

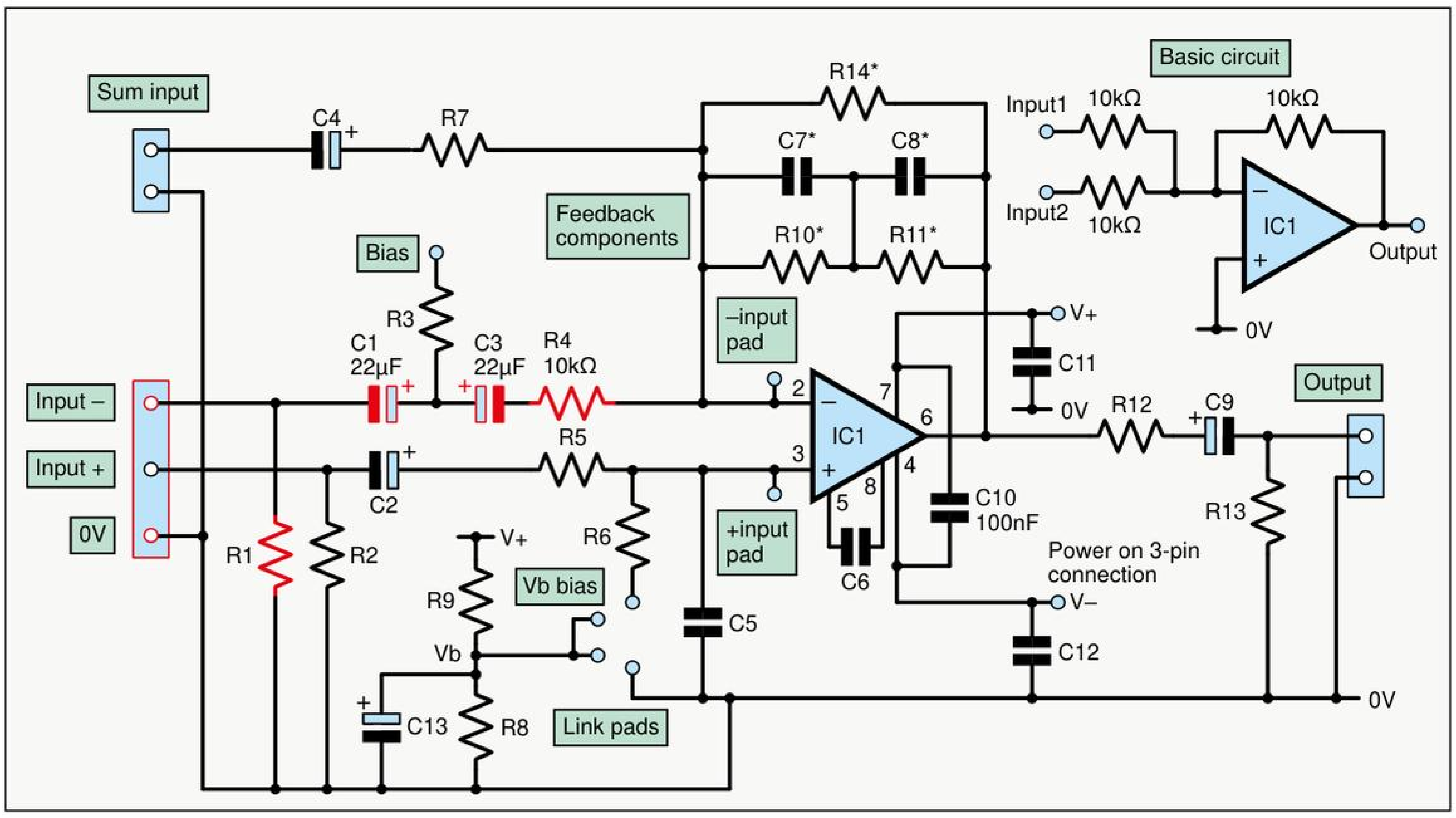
These are coupling capacitors on the op amp inputs. C1 and C3 are for the inverting input. They can be wired as a non-polarised capacitor for low distortion. The capacitor distortion can be reduced still further by biasing the mid-point positive terminals of C1 and C3 at 5V using R3 and Vb. C1 and C3 can also assume the role of the lower-arm feedback capacitor for non-inverting configuration when grounded by putting a shorting link in R1s position. C2 is connected to the non-inverting input.

R4

This is the input resistor for an inverting amplifier configuration, commonly designated 'Rin'. It can also be the negative-phase ('cold' in audio parlance) input resistor on a differential amplifier. R6 is usually linked to ground in inverting amplifiers via a link. A low value, such as 560Ω, is often used for audio for low noise while providing a degree of input current limiting in the event of faults such as power supply misconnection. In instrumentation, it is usually the same value as the feedback network giving lowest DC offset. For single-supply rail use, it is connected to the half-rail bias network consisting of R8 and R9 via another link. The link area is shown in Fig.7.

R5

This can be the positive phase input resistor on a differential amplifier. In the non-inverting configuration, it becomes the input RF filter in conjunction with C5.



Sum input
C4
R7
R14*
C7*
C8*
Basic circuit
Input1
10kΩ
10kΩ
Input2
10kΩ
IC1
Output
Feedback components
R10*
R11*
Bias
R3
C1 22µF
C3 22µF
R4 10kΩ
–input pad
V+
C11
0V
Input –
Input +
0V
R5
C2
2
3
7
6
4
5
8
0V
R12
C9
Output
R13
C10 100nF
R1
R2
V+
R6
+input pad
C6
Power on 3-pin connection
V–
Vb bias
R9
C5
C12
Vb
C13
R8
Link pads
0V

Fig.12. Summing or mixing amplifier with an extra input – the composite bipolar capacitor (C1 and C3) is optimised for good LF response. Note: red components shown are in addition to those in Fig.9.

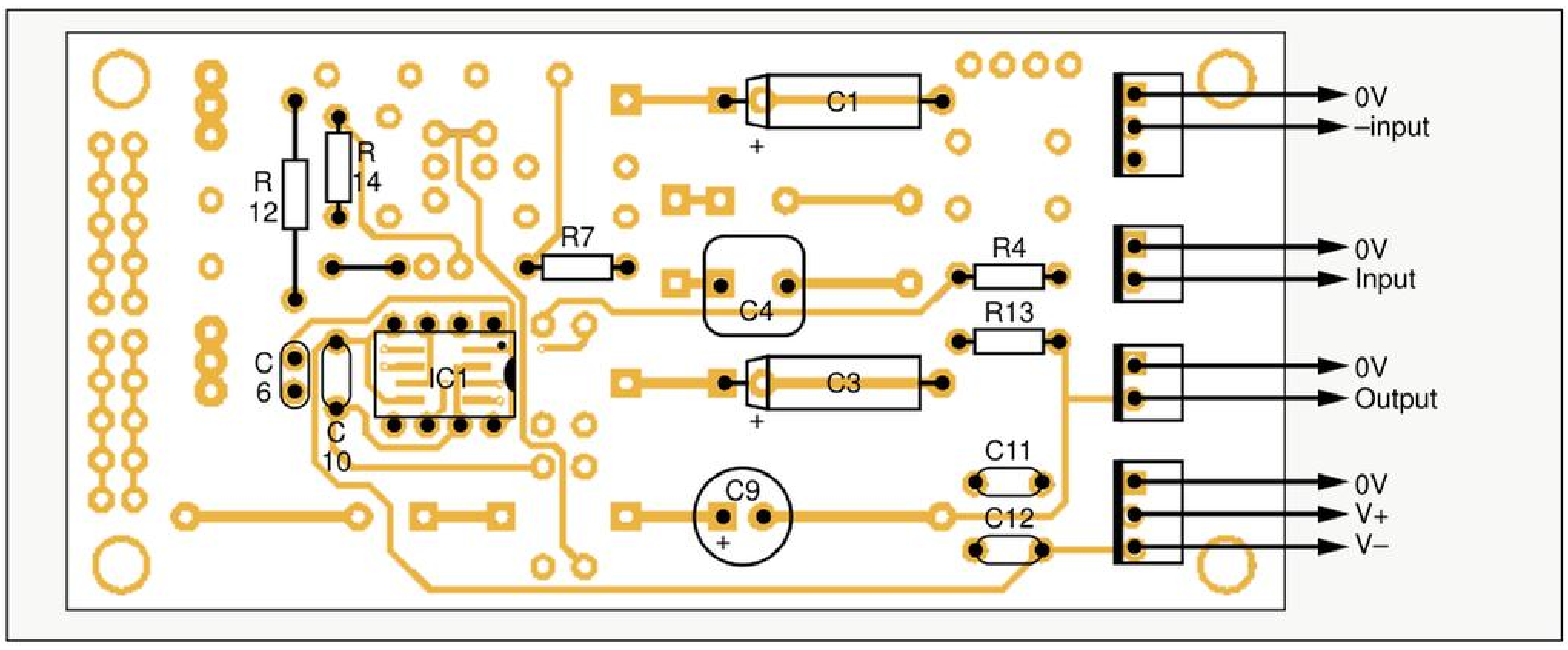
C4 and R7

These provide a second input to the inverting amplifier's input when used as a virtual earth summer or mixer.

R14

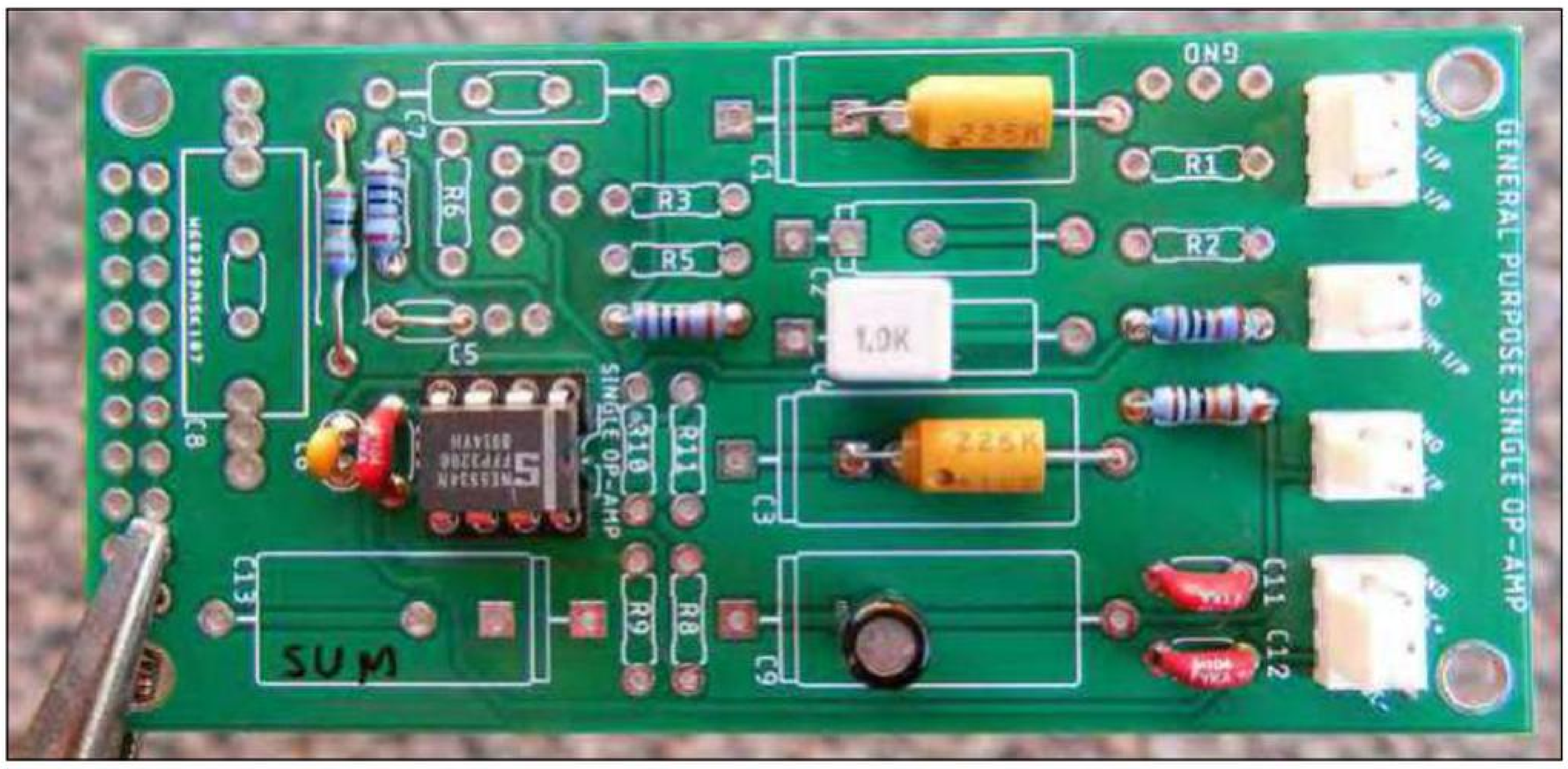
This is the all-important negative feedback resistor. There is provision for more complex feedback networks, such as RIAA equalisation comprising R10, R11, C7 and R8.

Finally some stability components. If a phase-lead capacitor is needed across feedback resistor R14, it can be C7 with C8 linked out. Typical values are 33 to 100pF. R12 is needed to isolate the op amp from capacitive loads, such as screened cables. An inductor can also be used instead for lower AF output impedance. This can consist of 40 turns of wire wrapped around a 1W 39Ω resistor or a 10µH inductor and resistor wired in parallel, as shown in Fig.8. There's the usual decoupling capacitors C10, C11 and C13. Capacitor C6 is the compensation capacitor for NE5534 op amps for gains below 5.



C1
R 12
R 14
R7
R4
C4
R13
C 6
IC1
C 10
C3
C11
C9
C12
0V
–input
0V
Input
0V
Output
0V
V+
V–

Fig.13. Overlay for summing amplifier.



GENERAL PURPOSE SINGLE OP-AMP
GND
R1
R2
R3
R5
C1
C3
C5
C7
R6
C8
R10
R11
R8
R9
C9
C13
C11
C12
SUM

Fig.14. The completed summing amplifier.

Component list (and function)

Semiconductors

IC1	Single op amp, such as NE5534. Can be 8-pin DIP through-hole or SOIC surface-mount part.

Resistors

All standard 0.25W case size, usually metal-film, use the 1% 0.6W MRS25 series for audio.

R1, R2, R3	input grounding/pull-down resistors 22kΩ to 100kΩ
R3	bipolar capacitor bias resistor or link to ground for using big lower-arm feedback capacitor in C3 position.
R4, R5	op amp input resistors, typically 1kΩ to 100kΩ
R6	non-inverting input grounding / bias resistor, typically 1kΩ to 100kΩ (much higher, 1MΩ to 4.7MΩ, for FET op amps)
R7	summing input resistor
R8, R9	half-rail bias resistors equal value, 10kΩ to 100kΩ
R10, R11	extra feedback resistors for filters
R14	feedback resistor zero to 220kΩ (much higher, 1MΩ to 4.7MΩ, for FET op amps)
R13	output capacitance isolation resistor 39Ω to 600Ω

Capacitors

C1, C2	input coupling capacitors, typically 1µF to 22µF
C3	part of bipolar capacitor with C1 or big lower arm feedback capacitor
C4	extra input coupling capacitor for summing input or small lower arm feedback capacitor

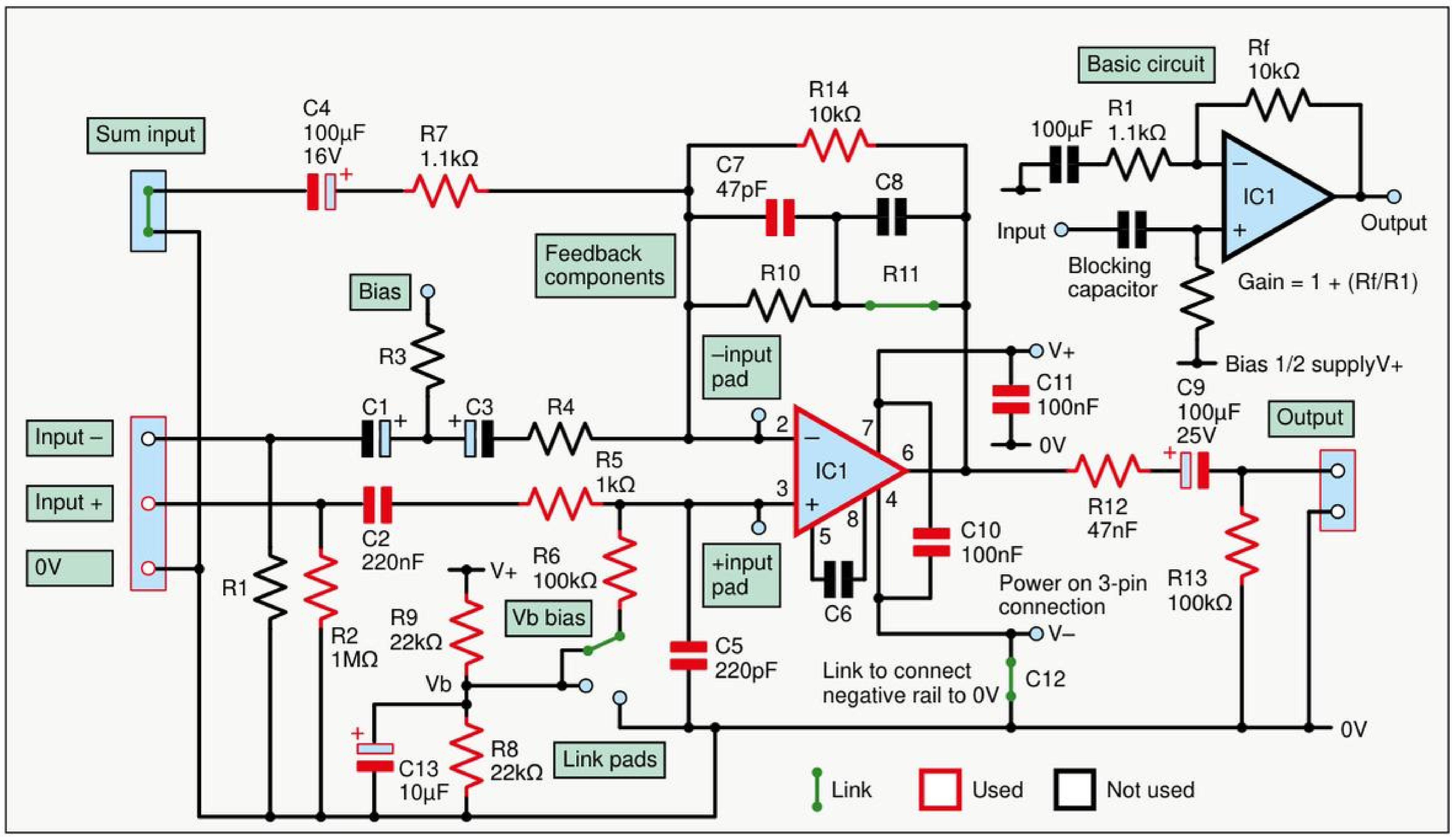

Sum input
C4
100µF
16V
R7
1.1kΩ
R14
10kΩ
C7
47pF
C8
Feedback components
R10
R11
Bias
R3
C1
C3
R4
–input pad
R5
1kΩ
IC1
2
3
7
6
4
8
5
Input –
Input +
0V
R1
R2
1MΩ
C2
220nF
V+
R6
100kΩ
R9
22kΩ
Vb bias
+input pad
C6
C5
220pF
Vb
C13
10µF
R8
22kΩ
Link pads
Link to connect negative rail to 0V
C12
Power on 3-pin connection
V–
V+
C11
100nF
0V
C10
100nF
R12
47nF
C9
100µF
25V
R13
100kΩ
Output
0V
Basic circuit
Rf
10kΩ
R1
1.1kΩ
100µF
Input
Blocking capacitor
IC1
Output
Gain = 1 + (Rf/R1)
Bias 1/2 supplyV+
Link
Used
Not used

Fig.15. Non-inverting amplifier with gain of 10x and single-rail biasing.

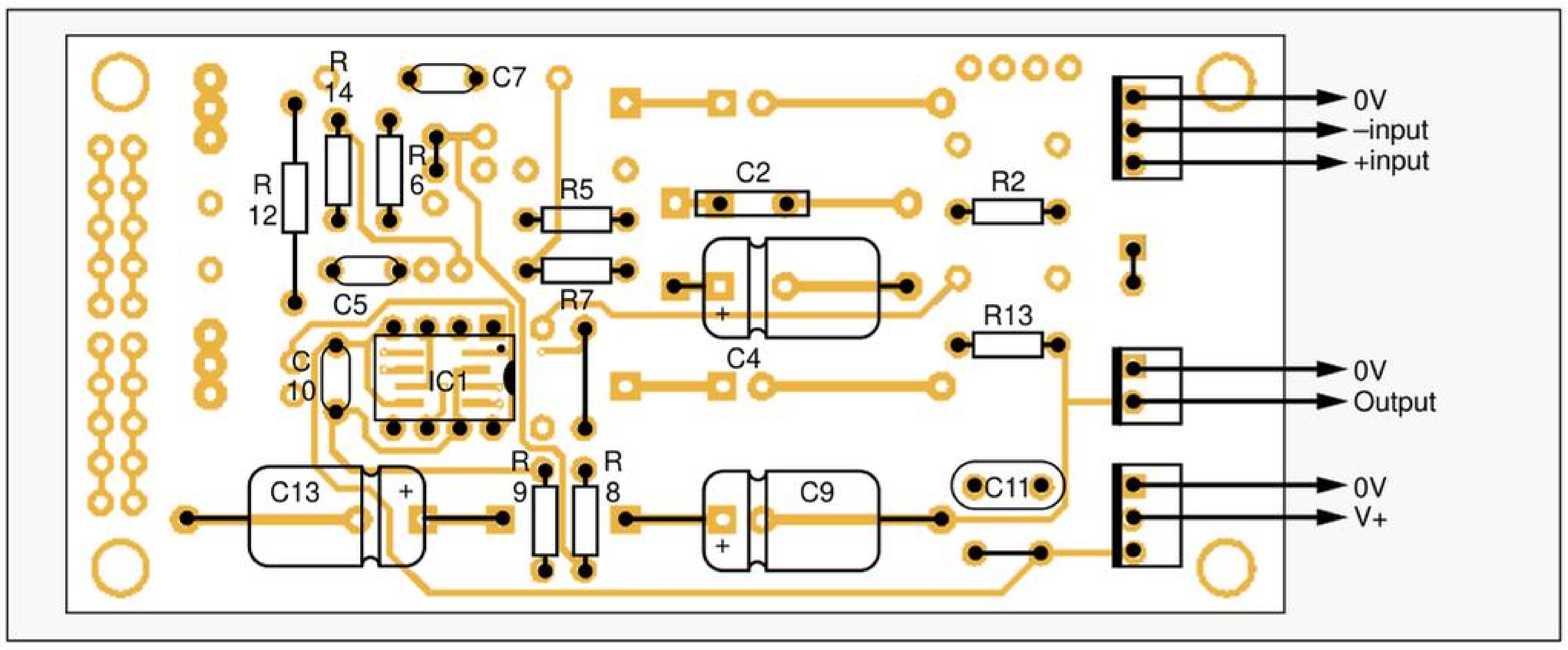

R
14
C7
R
6
R
12
R5
C2
R2
C5
R7
C4
R13
C
10
IC1
C13
R
9
R
8
C9
C11
0V
–input
+input
0V
Output
0V
V+

Fig.16. Overlay for non-inverting amplifier – note bias links.

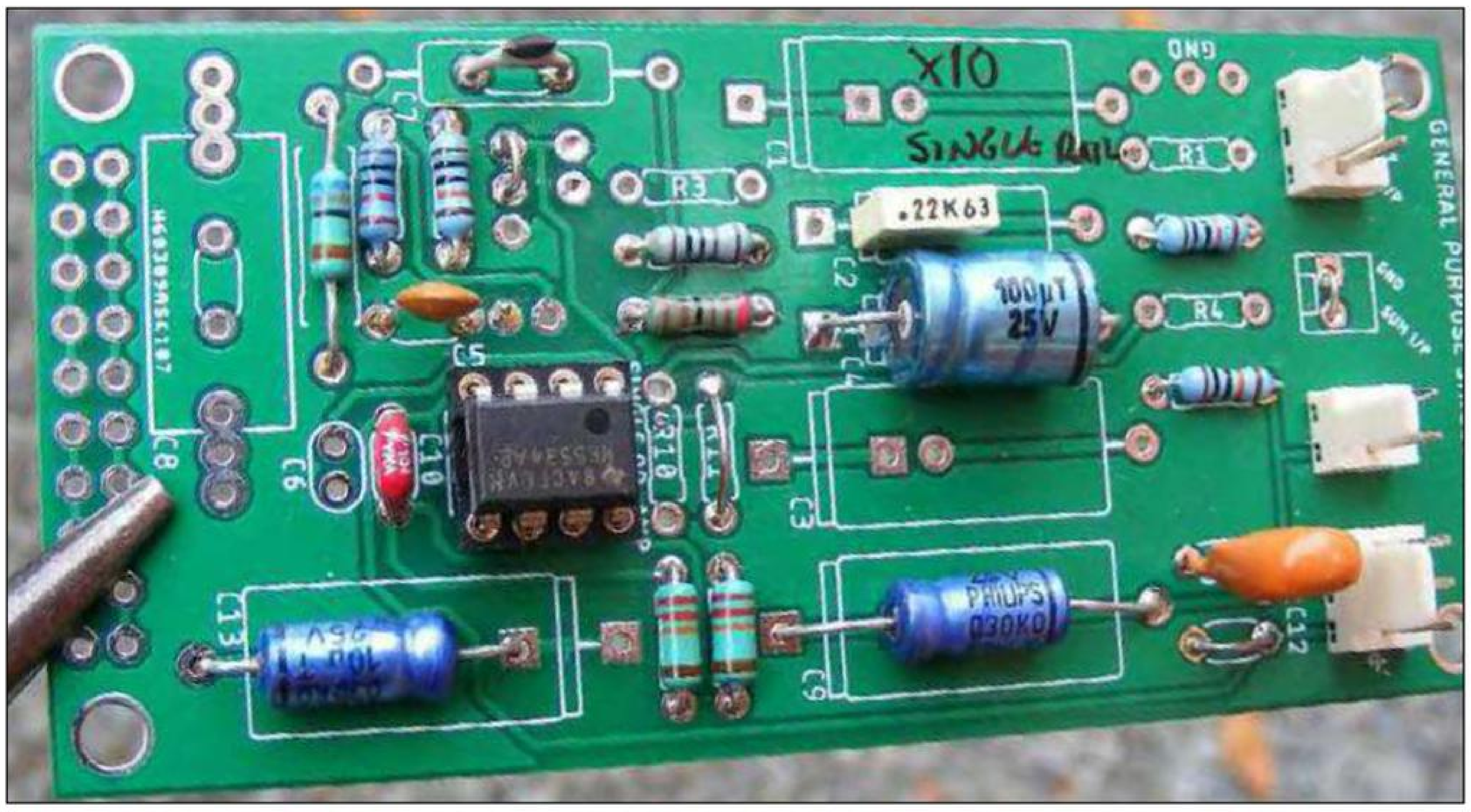

x10
SINGLE RAIL
R1
R3
R4
.22K63
100µF
25V
C5
C10
C9
C13
C12
GENERAL PURPOSE

Fig.17. Fully stuffed non-inverting amplifier.

C5	RF filter, 47pF to 470pF
C6	NE5534 compensation; not used for gains over 5: 22pF for unity gain, 4.7pF for RIAA stages, 2.5mm pitch
C7, C8	feedback, C8 is for extra-large polystyrene filter capacitors
C10	power rail decoupling 0.1µF ceramic 5mm
C11, C12	0.1µF ceramic 5mm or up to 10µF electrolytic

Connectors

Molex 0.1-inch pitch PCB connectors Molex equivalent 2 off each JYK P2500-02 two-pole straight header and three-pole P2500-03 Rapid order codes 22-0950 and 22-0955

Classic configurations

Here's a few of the possible circuits that can be built on the board; I'm sure readers will adapt the board for many other applications–do let us know your ideas.

Inverting amplifier

Apart from a voltage follower, this is the simplest amplifier circuit that can be built on the board. There are two ways of feeding the input. The simplest is to come in via the two-pin input Molex connector shown in the circuit in Fig.9 and the overlay in Fig.10. An alternative is to use the inverting input on the three-pin connector via C1. This enables a bipolar input coupling capacitor composed of C1 and C3 to be used. This network can be biased to give the lowest distortion. This is useful for low-impedance applications where the input resistor is very small. A completed inverting board is shown in Fig.11.

Summing amplifier

This is just an inverting amplifier with an extra input resistor. Both inputs on J1 and J3 are used. The circuit is shown in Fig.12. The bipolar capacitor set up was used for an equaliser where a low-pass filter output of a state-variable filter was mixed with the high-pass creating a notch filter. The high value used (11µF) minimised the LF response droop. The overlay is shown in Fig.13 and Fig.14 shows the construction.

Non-inverting amplifier

This is probably the most common op amp circuit, typically giving any gain from 1 to 1000 (0dB to 60dB) along with a high input impedance. A circuit giving a gain of 10x is shown in Fig.15.

This circuit is more complicated because it is shown designed for single-rail (rather than the normal dual-rail powering). This is achieved by feeding the non-inverting input with a half-rail bias voltage. The overlay is given in Fig.16. A useful application of this configuration is a microphone preamplifier. This consists of a non-inverting amplifier with variable gain and a step-up input transformer. Fig.17 shows the completed board. To run it off the dual-rail supply, leave off the half-rail bias and link R6 to ground.

Next month

In Part 2, we will finish describing this design with a differential and RIAA phono amplifier, plus a useful and unusual low-frequency compensated op amp amplifier.

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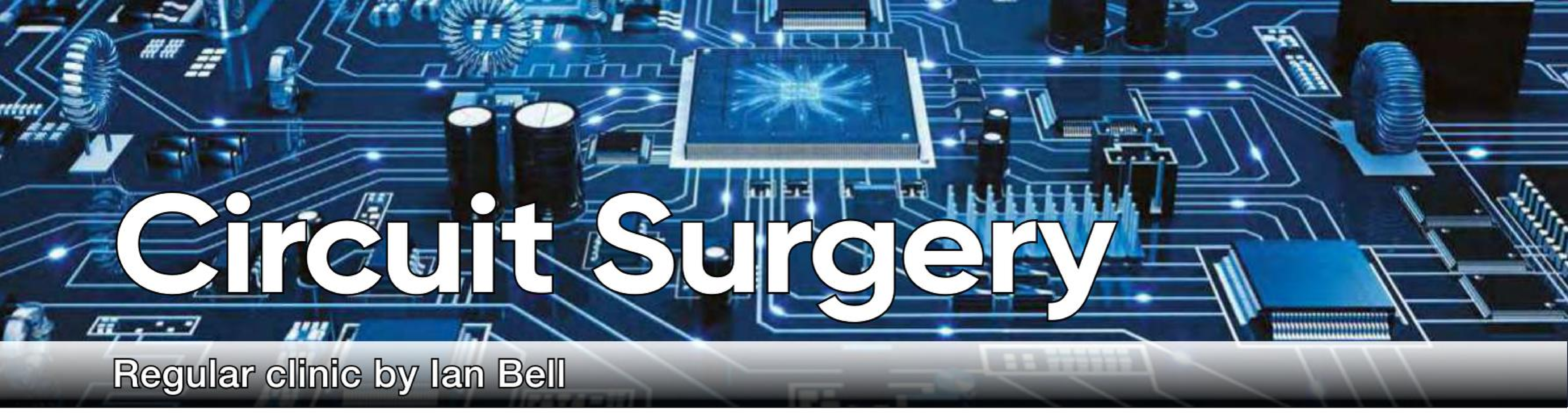

Circuit Surgery

Regular clinic by Ian Bell

Electronically controlled resistance – Part 4

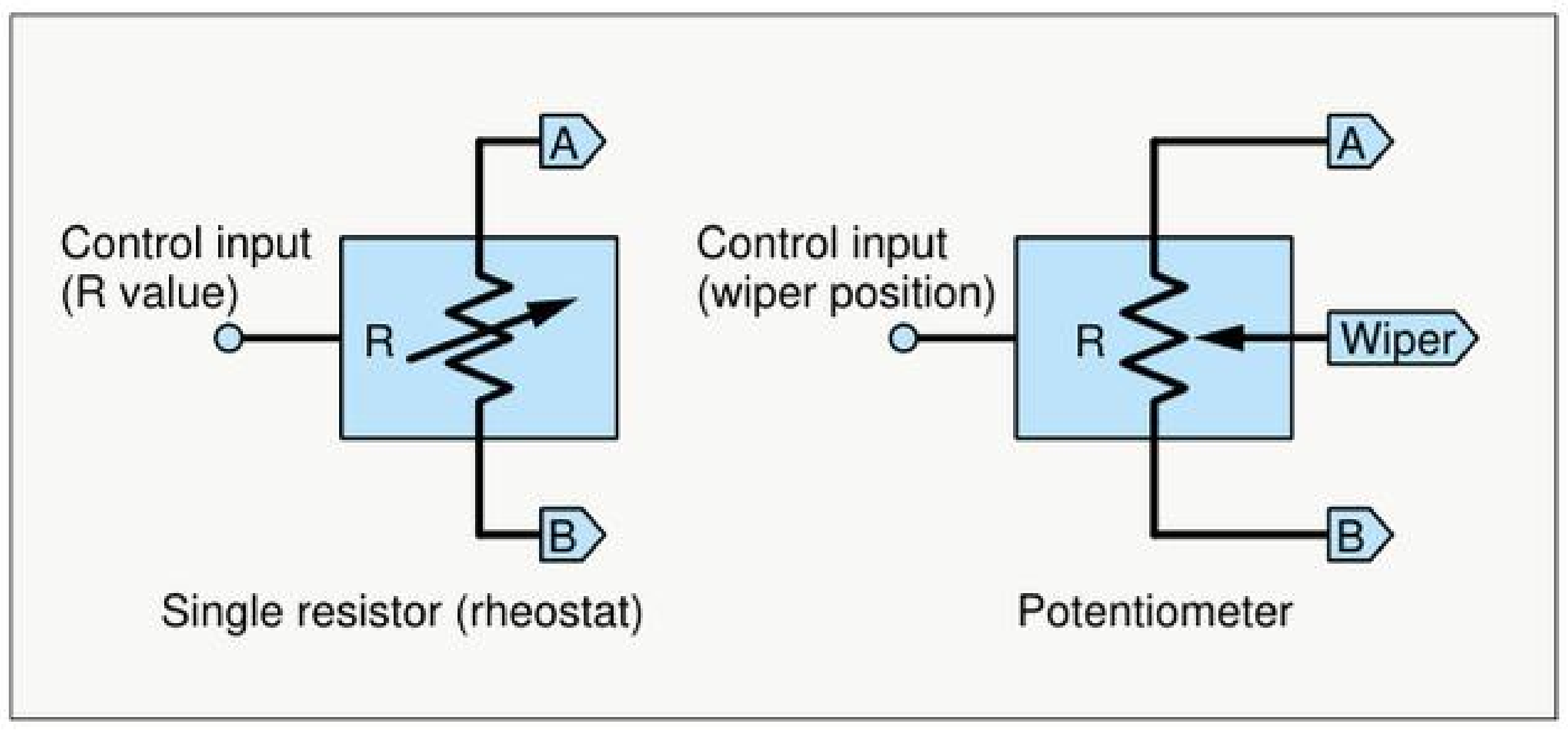

Fig.1. Basic digipot types: representing the electro-mechanical rheostat and potentiometer.

For the previous three months we have been discussing electronically controlled resistance, focusing mainly on the use of JFETs (junction field-effect transistors) as voltage-controlled resistors. This series was instigated by a post on the EEWeb forum about electronically controlling resistance, but not specifically about JFETs. Although JFETs (and sometimes other FETs) are commonly used as electronically controlled resistors, and have significant historical significance, they are not the most widely used approach in modern systems. So, this month we will look at 'digipots' – digital potentiometers – which are integrated circuits providing a similar function to mechanical potentiometers and trimmers.

Digipots are available in both rheostat and potentiometer versions (see Fig.1). Potentiometer versions can usually also be used in rheostat mode by using the resistance between the wiper and one of the ends (A or B). The resistance (rheostat) or wiper position (potentiometer) is controlled with a digital interface. Typically, digipots are controlled by a microcontroller, often via a serial bus such as SPI or I²C, but simpler interfaces which allow the resistance or position to be stepped up or down, as well as parallel digital inputs are also available. The number of steps (resistance values or wiper positions, often referred to as 'taps') is usually a power of two related to the number of bits in the digital control circuit, with the range of steps being typically from 32 (5-bit) to 1024 (10-bit) but fewer steps (4 and 16) and 100-step devices are also available.

The stepped nature of digipot adjustment is different from the theoretically continuous variation available from a film-based mechanical potentiometer or JFET electronically controlled resistors. Real mechanical potentiometers are not perfect so do not have an infinite effective number of steps. Their effective resolution and repeatability (the accuracy with which the same value can be set after moving away) may be about 0.5% to 1%. Multi-turn mechanical potentiometers provide better resolution (finer adjustment) at higher cost. Wirewound mechanical potentiometer have lower resolutions because the wire turns effectively create mechanical steps in the resistance value. The resolution of an *N*-step digipot is 100/*N*%. For example, with an 8-bit control word this is $100/2^8 = 100/256 = 0.4\%$.

Digipot circuit

Before discussing digipot devices or parameters further it is useful to look at a basic digipot circuit, as this provides insights to their characteristics. Fig.2 shows a digipot implementation concept diagram – it is not intended to represent a specific device. The potentiometer comprises a set of resistors connected in series between A and B – this arrangement is often referred to as a resistor ladder. The total resistance between A and B is fixed and is referred to as the end-to-end resistance, or simply the resistance of the digipot. This resistance varies widely for available devices – for example, from 1kΩ to 1MΩ – but devices with 5kΩ to 100kΩ resistance are more common. Often, a given IC will be available in a few different resistance values.

The wiper is implemented using a set of electronic switches. One of the switches will be on to determine the wiper position, all the other switches are off. The A, B and wiper (W) connections correspond with the standard potentiometer symbol shown in Fig.1. The wiper switches connect to all

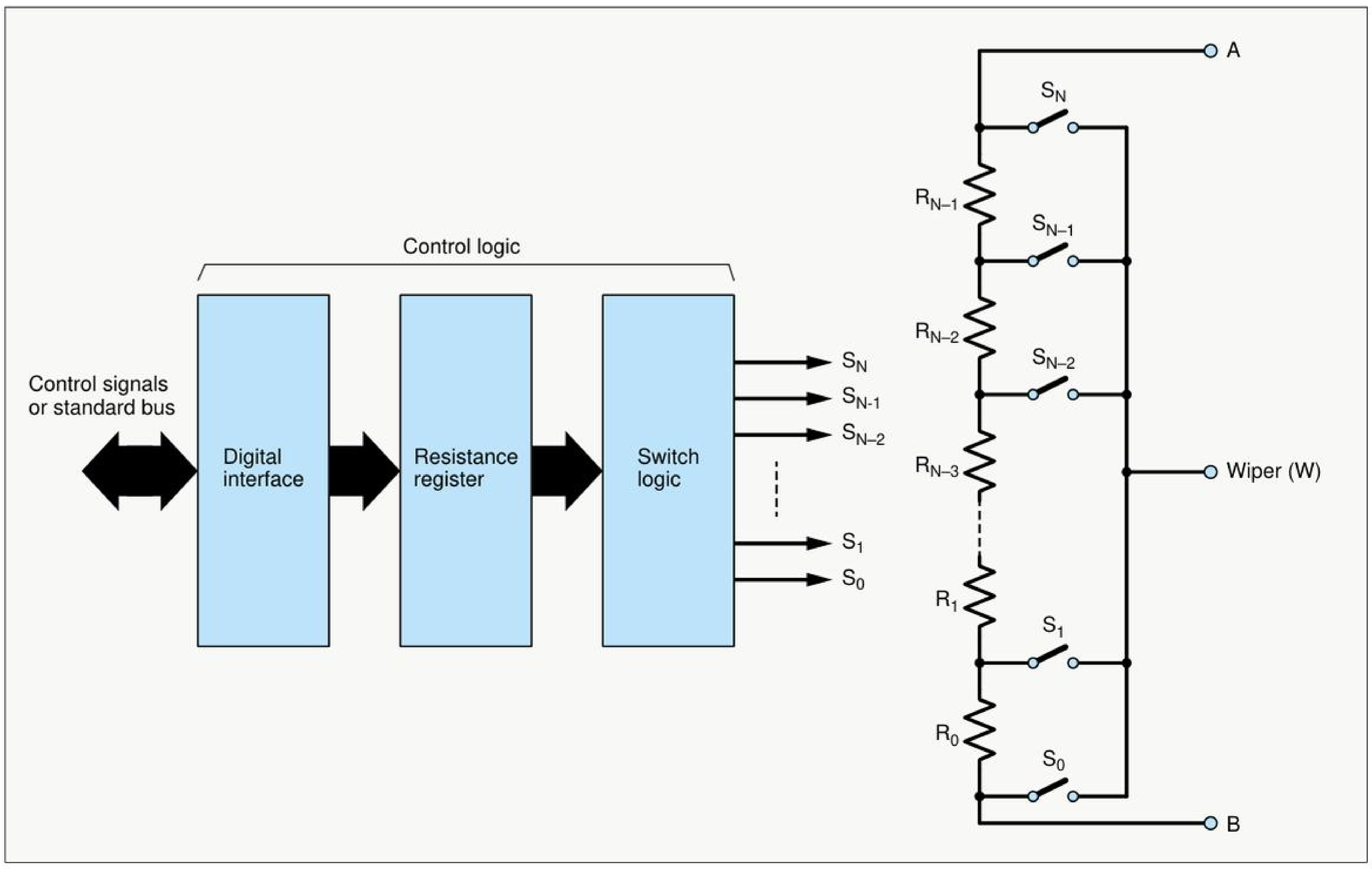

Fig.2. Circuit concept for implementation of a digipot.

the points between the resistors in the ladder, so they are often referred to as ‘taps’. The switches are typically implemented using MOSFETs (transmission gates using an N and P transistor in parallel).

Which switch is on is determined by the control logic. In the circuit in Fig.2 the resistance register holds a binary number controlling the wiper position. This is decoded by the switch logic to determine which single switch is on. The register value is set to the required wiper position value by the user via the interface logic. The interface can take a number of forms, as already noted, and standard serial buses and up/down controls are common. Digipot ICs may have multiple potentiometers on a chip (typically 2, 4 or 6).

Resolution and variations

The number of resistors between A and B (Fig.2) determines the resolution of the potentiometer and hence the number of bits required in the resistance register. If all the resistors have the same value, called the step resistance (R_S), then the resistance from the A or B to the wiper (R_{AW} or R_{BW}) will have a linear relationship with the resistance register value – this is called a ‘linear taper’.

It is also possible to scale the resistor values so that the resistance from the A or B terminals to the wiper varies logarithmically with the resistance register value (called a ‘log taper’). The linear and log taper options directly correspond with linear and logarithmic mechanical potentiometers. Logarithmic potentiometers are frequently used in audio equipment as volume controls because of the logarithmic response of the human ear to the loudness of sound. Using a volume / gain control with a logarithmic taper digital pot will change the signal level in constant *decibel* steps (eg, 1 dB per step).

There are variations possible in the number of resistors and wiper taps for digipots with a similar resolution. If we have a 7-bit resistance register then there are $2^7 = 128$ possible values, which means that 128 switches can be controlled. Fig.2 shows N+1 switches (labelled S_0 to S_N) for N resistors (labelled R_0 to R_{N-1}) in order allow the wiper to be connected directly to both the A and B terminals – this corresponds to what would usually be the case for a mechanical potentiometer where the wiper is connected directly to the terminals which are at the extremes of the shaft movement. Thus, a 7-bit register would control a ladder of 127 resistors.

Taking terminal B as a reference, if S_0 is on we have a nominally zero resistance from B to the wiper (R_{BW}) – this is referred to as the zero-scale setting. With S_N on we have the maximum R_{BW} equal to $N \times R_S$ for a linear taper. This is the full-scale setting.

Designers may prefer to have a ladder with 128 rather than 127 resistors. This can be achieved either by using an 8-bit register (the digital wiper position binary value ranges from 00000000 to 10000000), or by still using 7 bits and removing one of the switches (to terminal A or B) shown in Fig.2. The latter option means that the wiper cannot connect directly to one of the terminals – the wiper-to-terminal resistance (R_{AW} or R_{BW}) at that end cannot be set to a nominal zero value. These general arguments apply to other resolutions, for example 8 or 9 bit register and 255 or 256 resistors. Which of these options applies will depend on the digipot device and designers should be aware of this and the implications for their design in terms of resistance/wiper control range, step value and software requirements related to the number of bits used.

Memory

If a mechanical potentiometer is set to a particular value and the circuit is switched off, then its setting will be the same when the circuit is next switched on. The mechanical potentiometer ‘remembers’ its setting, unless of course someone moves it deliberately or inadvertently while the circuit is off (easily done with a front-panel control knob). The same applies to mechanical trimmers, with less likelihood of inadvertent adjustment as they are usually less accessible and less easy to knock out of position.

A basic digipot will forget its wiper position setting when power is removed. Typically, the circuit might have a power-on reset which determines a specific initial setting (for example, resets the resistance register to zero). This may not provide optimal conditions at start up – for example, a volume control which is always set to zero at power on may not provide the best user experience.

For systems where the digipots wiper settings are controlled using a microcontroller (a common scenario) the wiper positions could be stored by the processor in non-volatile memory (memory that retains data when power is removed) and restored at system power-up. The problem with this approach is that it takes time for the software to configure the system, particularly if there are several digipots and other initialisation routines to deal with. This means that the digipots will be temporarily in a default setting before being adjusted to the required value. The default values may be inappropriate, particularly where the digipots are used as trimmers to set adjustments, such as bias voltage, offsets and gain settings. In some cases, the inappropriate initial values, or dramatic changes during initialisation, may cause instability, glitches or even system malfunction. The problem does not occur with mechanical trimmers because they will have the correct value at power-up.

The solution to the problem of a digipot having the wrong value at power up it to use non-volatile memory on the IC itself and a number of devices provide this facility. The digipot retains the wiper setting it had at power-off and restores this immediately at power-on. Some devices provide a one-time programmable (OTP) memory so that a specific wiper position can be set during initial system configuration. The OTP value may set the wiper position always used at power-up, or it may provide a permanent setting so that the wiper position cannot be changed. This is typically used for circuits requiring a one-off calibration.

The AD5243 digipot

As mentioned above there are various control interfaces available for digipots. We will look at three example devices to provide some idea of the various options. Fig.3 shows a block diagram of the AD5243 series of I^{2}C digipots from Analogue Devices (typical price is around £3.25 from Mouser or DigiKey). The AD5243 is a 10-pin device that contains two 256-position potentiometers and is available with end-to-end resistance values of 2.5kΩ, 10kΩ, 50kΩ, and 100kΩ. it is aimed at replacing mechanical trimmers for functions such as level setting, bias and offset adjustment, sensor adjustment and gain control. The control interface is an I^{2}C serial bus, which only requires two wires – clock (SCL)

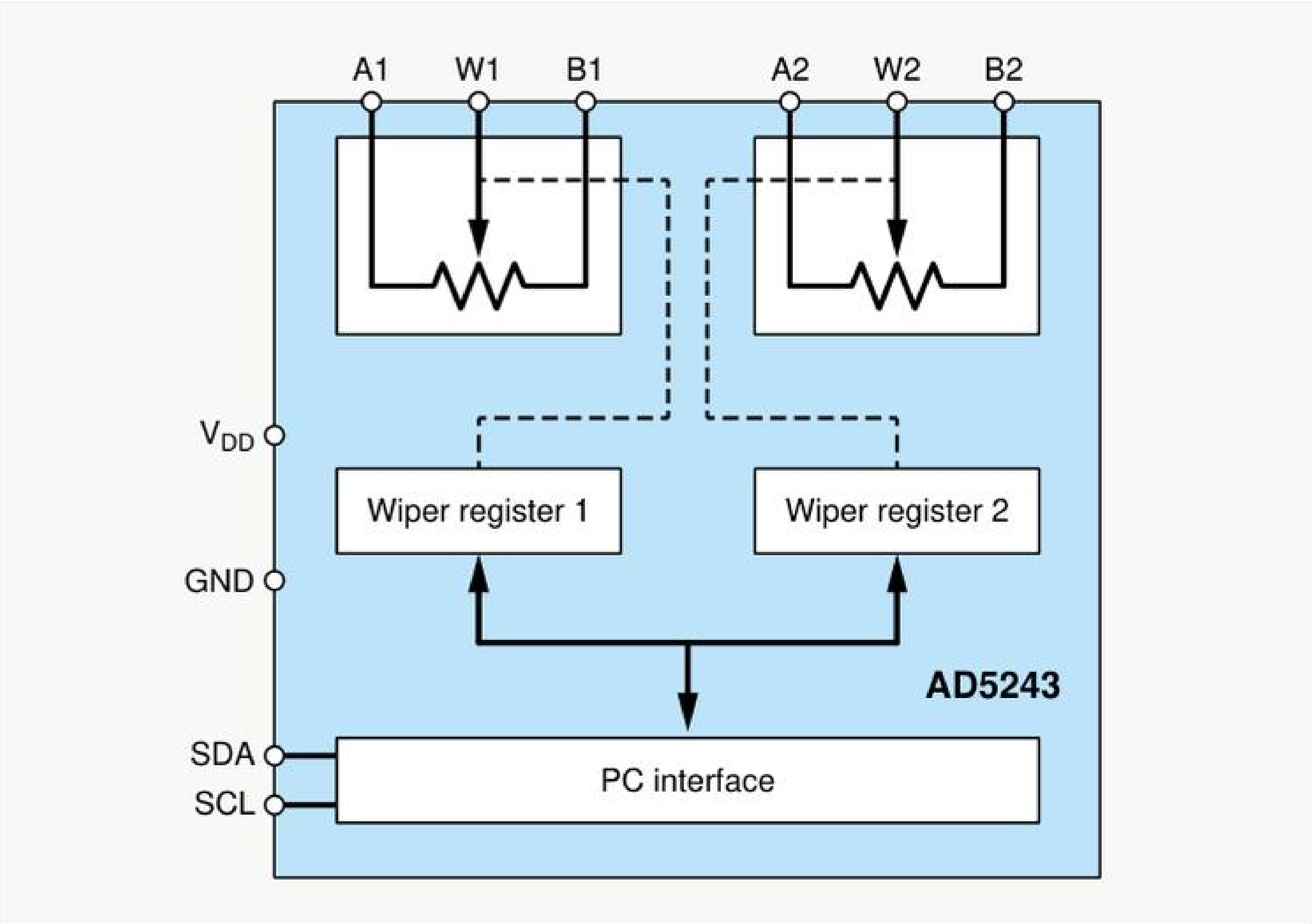

Fig.3. AD5243 block diagram, an I^{2}C-controlled dual 256-position potentiometer.

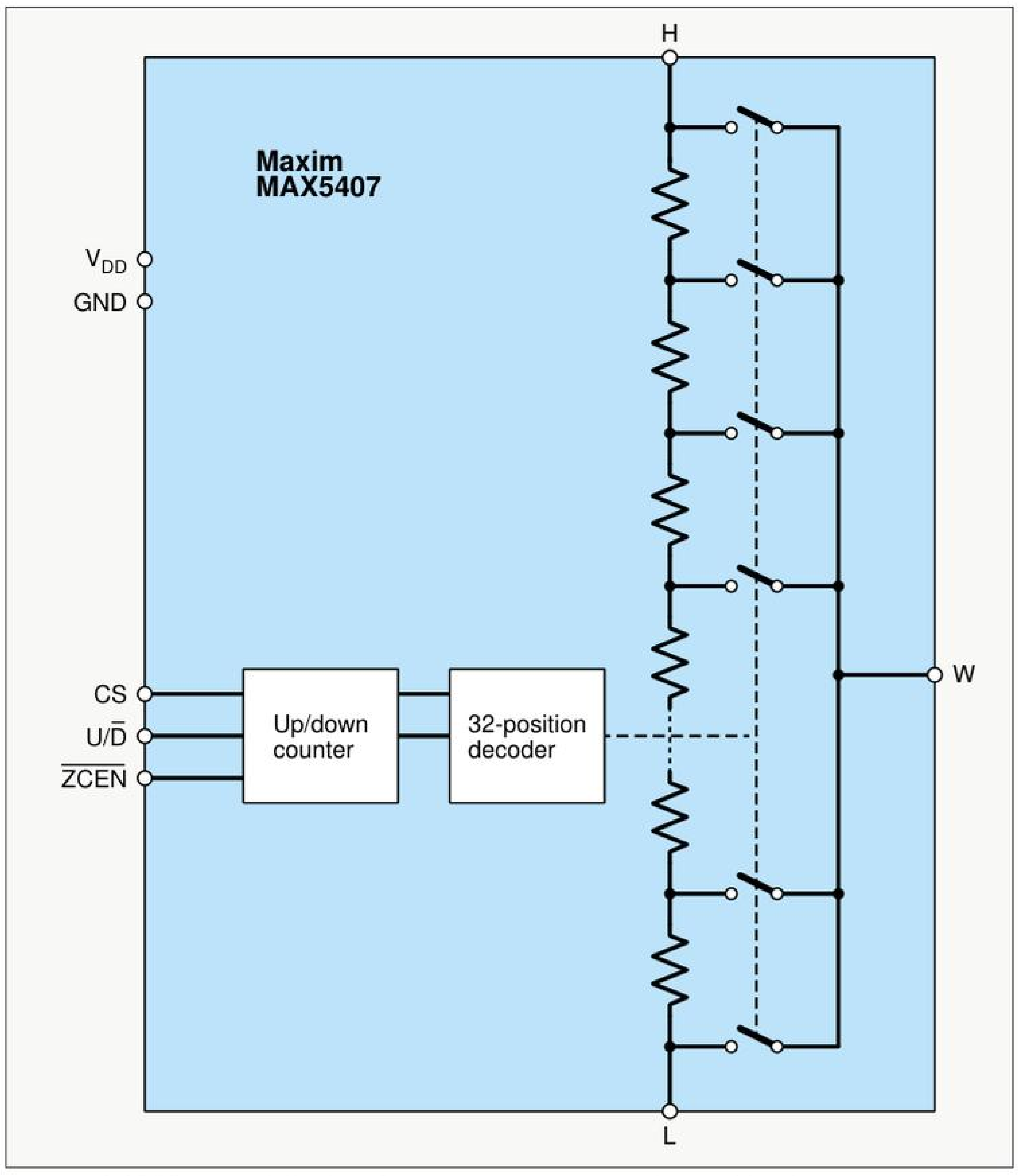

Fig.4. MAX5407 block diagram, a 32-tap logarithmic taper digipot with 1dB steps.

and data (SDA). A similar device, the AD5248 (similar price) provides two rheostats and has address pins allowing multiple devices to share the same I²C bus. Usually, the I²C bus would be connected to a microcontroller and software running on that device would control the potentiometer wiper positions.

The wiper positions for the AD5243 are set by writing an 8-bit value via the I²C along with a single address bit indicating which potentiometer is being controlled. The current wiper position can also be read from the device via the bus. The potentiometer can be put into a shutdown mode via a control bit. This sets an open circuit at terminal A and shorts the wiper to terminal B. The AD5243 does not have a non-volatile memory but has very low power consumption (1.3µA supply current) so could be kept powered up when the rest of the system is off in order to retain the wiper setting (this approach is discussed in the device datasheet).

The MAX5407 digipot

Fig.3 shows a block diagram of the MAX5407 from Maxim Integrated (now a subsidiary of Analog Devices, typical price is around £2.50 from Mouser or DigiKey). The MAX5407 is a logarithmic taper single digipot potentiometer with 32 tap points configured to have 1dB steps between taps. It has an end-to-end resistance of 20kΩ. The MAX5407 is aimed at replacing mechanical potentiometers in audio applications, for controls such as volume and balancing. At power on the device resets to the lowest tap position (wiper switch closest to L pin on), it does not store its previous setting in non-volatile memory.

A problem that can occur with digipots in audio applications is an audible click when the wiper position is changed. To address this issue the MAX5407 features a zero-crossing detector. Changing the wiper at the point the audio waveform is crossing through 0V prevents sudden signal level changes which can be heard as clicks. When this is enabled by taking the ZCEN pin low the MAX5407 waits for up to 50ms for zero voltage across the digipot (between the L and H pins) after receiving an input to change the wiper position. The wiper is changed when zero crossing is detected or after 50ms if one does not occur in that time.

The wiper position of the MAX5407 is controlled by an up-down counter. The value in the counter is changed via the U/D and CS pins. The direction of counting (up or down) is set by the value on U/D (one for up, zero for down) when the CS pin changes from zero to one (positive edge on CS). After this, while the CS pin remains high, the counter can be incremented or decremented using the U/D pin. Each zero-to-one transition (positive edge) on U/D will change the count value and hence wiper position by one step up or down depending on the direction set by the CS transition. When CS is low, changing the wiper is disabled and it maintains its position.

The DS1809 digipot

Fig.5 shows a block diagram of the DS1809 'Dallastat' digital potentiometer, also from Maxim/Analogue Devices, typical price is around £10 from Mouser or DigiKey. Note that despite being costlier, unlike the other two devices mentioned above, which are strictly surface-mound devices, the DS109 is available in an 8-pin through-hole package. The DS1809 is a 64-position linear digipot, available with end-to-end resistance values of 10kΩ, 50kΩ, and 100kΩ. It is aimed at replacing mechanical potentiometers in general applications. The DS1809 has an on-chip non-volatile memory for the wiper position.

The control interface to the DS1809 is designed to facilitate simple pushbutton control of wiper position – so it does not require a microcontroller or any software development. However, the interface can be easily controlled by a processor if desired. For pushbutton operation the input pins UC (up control) and DC (down control) are connected to the switches, as shown in Fig.5. External switch debounce circuitry is not required for correct operation. The DC and UC pins are pulled up (by resistors in the device), so pushing the switches creates a low pulse on the input.

A pulse on one of the inputs (DC or UC) which is longer than 1ms but less than 0.5s will cause the wiper position to increment (UC) or decrement (DC) by one position. Repetitive pulses (to zero) must be separated by 1ms (high input) or they will be ignored. A low input longer than 0.5s is interpreted as a 'push and hold' and will cause the wiper to change position by one step every 100ms to facilitate quick adjustment over a larger range. Once the wiper has been moved to one end it will stay there if further inputs for the same direction are received.

For the DS1809 to store the wiper position in its non-volatile memory at power-down an external capacitor and Schottky diode are required, wired as shown in Fig.6. If the DS1809 is controlled by a processor, then wiper position storage can be instigated via the STR pin without the external diode and capacitor.

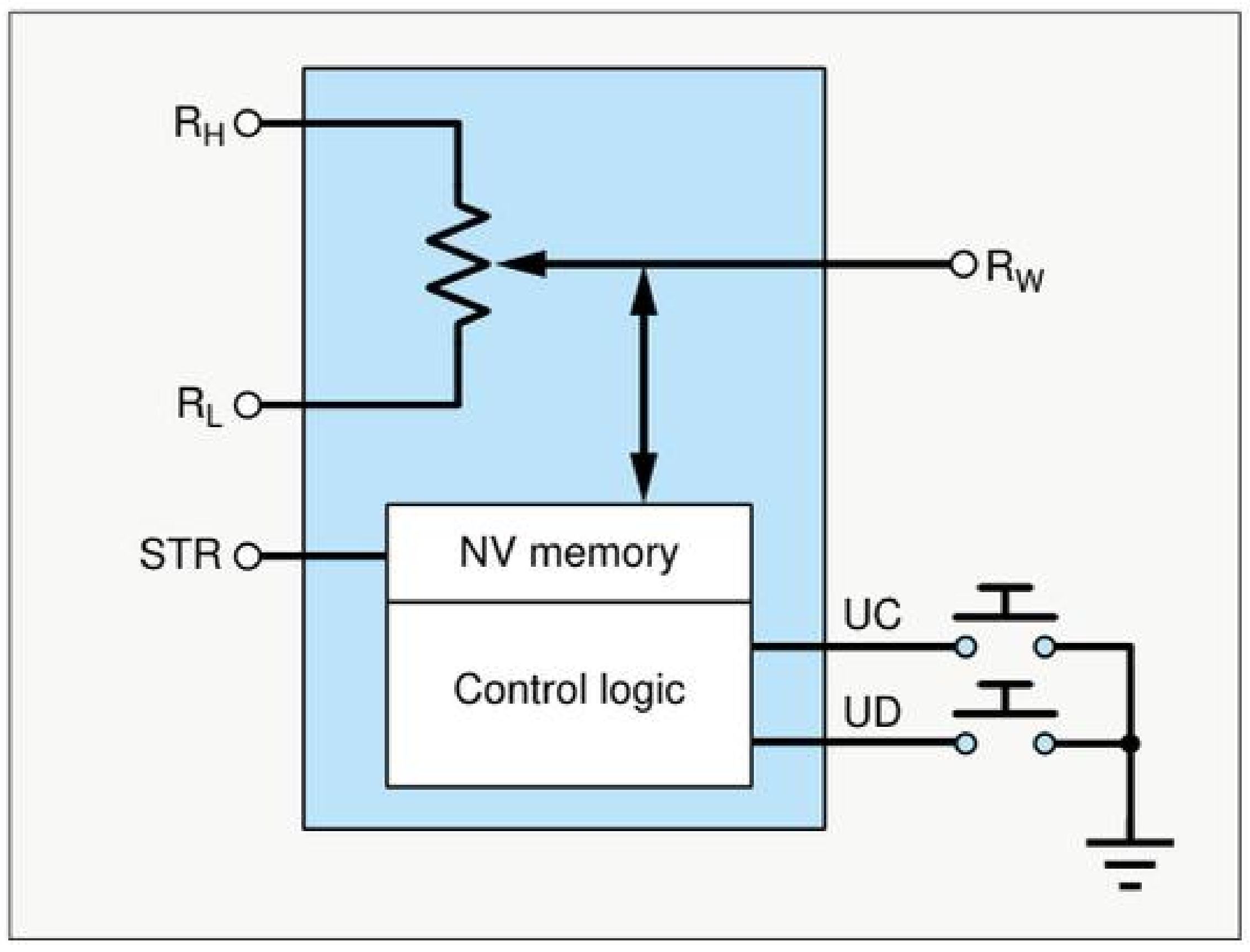

Fig.5. Block diagram of the 64-position linear digipot DS1809.

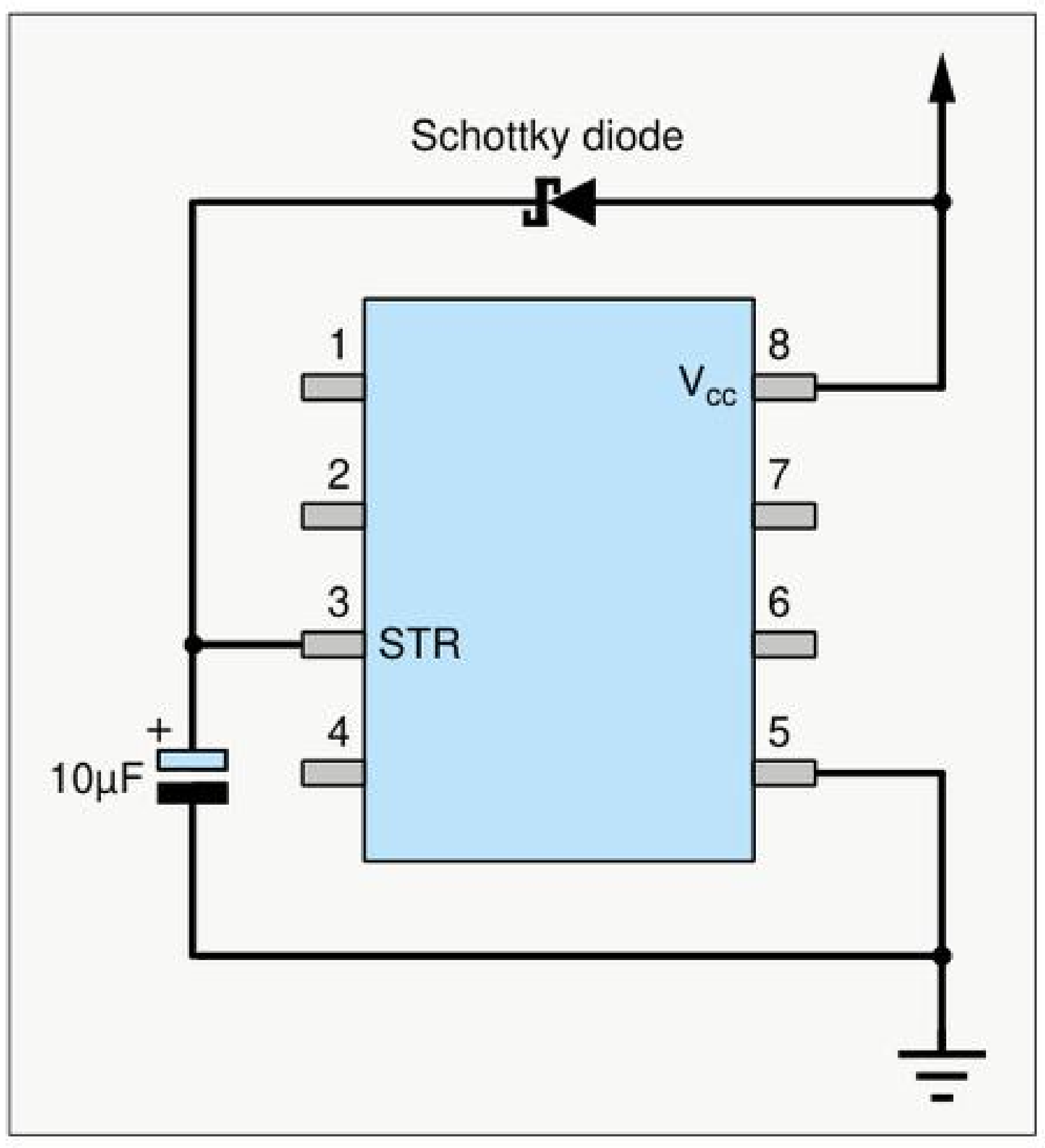

Fig.6. DS1809 block diagram showing the addition of an external capacitor and Schottky diode to store the wiper position in its non-volatile memory at power-down.

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Part 42: PicoMite Fingerprint Reader – Part 1

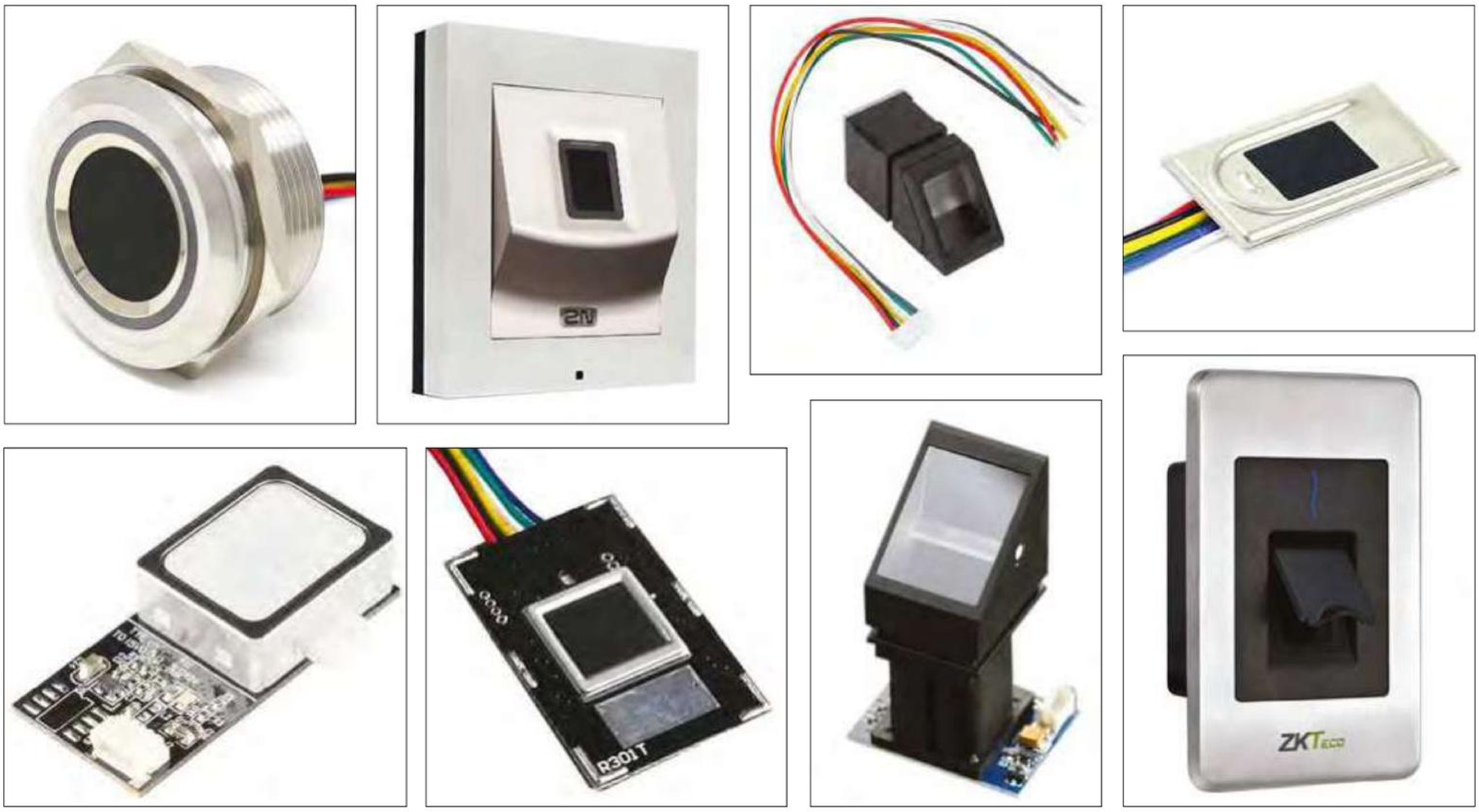

Fig.1. Various fingerprint modules are readily available online, priced from £15 upwards. We are using the R503 model (top left) in this article, which costs around £22.

Being able to recognise different fingerprints is a useful biometric feature to add to an electronics project, especially one that involves an element of security. By identifying different people from their unique fingerprint, it becomes possible to distinguish between authorised and unauthorised users, thus allowing a specific action to be performed (or not). Real-life examples of how fingerprint readers are used include: controlling access to a locked door (via a solenoid or electromagnet), turning on a device such as a computer, or even triggering a cashless payment.

So, how could we have fun with a fingerprint reader in a project closer to home? Perhaps the classic *Electronic Combination Lock* project (*PE*, December 2019) could be updated, or maybe you could switch your home-security system on and off. Whatever the application, a fingerprint reader must primarily be capable of reading a fingerprint, and then determining who it belongs to, and hence if it belongs to an authorised user, or not.

Fingerprint modules

If you search online, you will see that there are many fingerprint modules readily available – see Fig.1 for some examples. They start from around £15 for something basic that a hobbyist might use, to units costing many hundreds of pounds which are designed for commercial use. Even the cheaper fingerprint modules pack an impressive number of features and capabilities. For example, they typically contain either an optical or capacitive sensor, which feeds image data to an onboard microcontroller for converting any detected finger into a ‘template’ pattern. Some fingerprint modules include other elements such as LEDs, a sounder, or a vibration-motor for tactile feedback.

It must be stressed that the main element of a fingerprint module is the sensor that can detect a finger, and subsequently generate 'image data' from the fingerprint placed on the sensor. Typically, a fingerprint module needs to be connected to some form of intelligence to create a complete fingerprint reader unit that can decide what to do with captured image data. Generally, the cheaper fingerprint modules are connected to something like an Arduino, or Raspberry Pi, for which some basic example software (or experimental code) is available for download. However, the datasheets for these cheaper fingerprint modules tend to contain errors, and hence any downloadable software is often incomplete, or simply won't work at all; but occasionally you might come across some application software with functionality that actually does what it is meant to do!

I was recently sent a low-cost fingerprint module in error(!), so I set myself the challenge of hooking it up to a PicoMite (instead of the usual Arduino or RPi). Armed with a couple of different (contradictory) versions of the datasheet, I was determined to get it working. After connecting it up, I started writing some simple MMBASIC code to see if I could get a response. Remember that a fingerprint module contains an onboard microcontroller, so the PicoMite needs to send valid commands that the fingerprint module recognises for it to do anything. After a short while I had successful communication, and from that point on, all I had to do was work through the steps outlined (very poorly) in the datasheet with the aim of creating a standalone PicoMite fingerprint reader; and there – thanks to the poor documentation – is where the real fun started!

With patience, I made progress, and this month we will show you how to connect a low-cost fingerprint module to the PicoMite. We will then look at the structure of any message that is either sent to, or returned from, the fingerprint module. And by using a simple program we have written, you will be able to send any valid command that the fingerprint module recognises, and also know how to interpret the response it sends back.

Before we start, here's some terminology which will help clarify how to use a fingerprint module.

Fingerprint module vs fingerprint reader

A fingerprint module comprises a sensor, and an onboard microcontroller. By sending any valid command to its microcontroller, the module can be made to perform a specific task. Two main tasks that the module can perform are detecting a finger placed on the sensor and extracting image data from a fingerprint placed on the sensor. Another capability (for the module we'll be using) includes controlling a built-in ring LED located around the sensor. Note that the module needs to be told what task to perform by an external intelligent controller.

When a fingerprint *module* is connected to an intelligent controller, the result is a complete fingerprint *reader* unit that can do something useful. The controller sends commands to the module and the module performs the necessary task. On completion of the task, a response is sent back to the controller. By sending a precise sequence of tasks to the module, specific actions can be performed, resulting in a functional reader.

Image data vs template pattern

Once a finger has been detected, the intelligent controller sends a command to the module (ie, a task request) to generate image data of the fingerprint located on the sensor. Generally, two images are taken and these are 'averaged' to create a template pattern. This new template pattern is compared with stored template patterns when determining a user's identity. Each template pattern is stored alongside a unique ID number, and any matched template pattern returns the corresponding unique ID number in the response back to the intelligent controller (more on this next month). Note that we will often refer to a template pattern simply as a 'template'. Templates are essential for successful operation of a fingerprint reader; without stored templates it is not possible to determine who the user is, and hence whether they are authorised. The template pattern generated is either stored internally in the module's memory (along with any other templates) or it can be uploaded to the attached intelligent controller to be stored elsewhere. Note that we don't need to upload templates to the PicoMite as the fingerprint module we are using has enough memory to store up to 200 templates.

Enrolment vs Searching

To register a new user (ie, store a look-up template for them), a process called 'enrolment' is performed. Enrolment means that their template is generated (from two sets of image data) and then stored against a unique ID number. A precise sequence of specific tasks sent by the intelligent controller results in enrolment being performed.

'Searching' is simply the action of comparing a fingerprint with stored templates. A response back to the intelligent controller will confirm whether a match was found (or not). If a match is found, then the user is identified, and the intelligent controller can decide if the user is authorised (or not), followed by appropriate action.

The R503 module

We will now look at the specific fingerprint module that we will be using, the R503. The choice was a simple one – it was the model sent to me in error when ordering a GPS module! Checking the datasheet (available for download from the December 2022 page of the *PE* website), it appeared to be an excellent module, offering some nice features, with the bonus of a low price – around £22.

The R503 is built into a rugged metal body which makes it very easy to panel mount; something a lot of modules overlook. It inserts into a 24mm-diameter hole, affixed with an included nut. It is based on a capacitive sensor, which is generally regarded as performing better than an optical sensor. There is a built-in digital signal processor (DSP) chip which simplifies overall use since it performs all the algorithms normally associated with fingerprint processing. This mean that we won't get involved with any of the 'complex stuff'.

The R503 module is a serial device that communicates with an external controller, in our case, the PicoMite. Serial data is sent at a default baud rate of 57,600 (which can be changed if needed). It can operate at 3.3V, which is perfect for us since the PicoMite has a maximum input voltage on any I/O pin of 3.6V. Operational current consumption is low at 20mA, and it has an average sleep current of 2μA should it need to be powered from a battery. It can store up to 200 fingerprint templates in its own Flash memory, and it also has a built in bi-colour LED which provides a nice ring effect around the sensor. On the module sent to me, there is a red/blue bi-colour LED, so purple can also be generated. However, while researching this project, I read that other colour LEDs may be supplied instead. Note that most operational features of this fingerprint module (including the bi-colour LED) are controlled by commands that are sent to it from the attached intelligent controller (ie, the PicoMite). For testing purposes, we will use the LED as a visual confirmation to ensure we are communicating correctly with the module – see later.

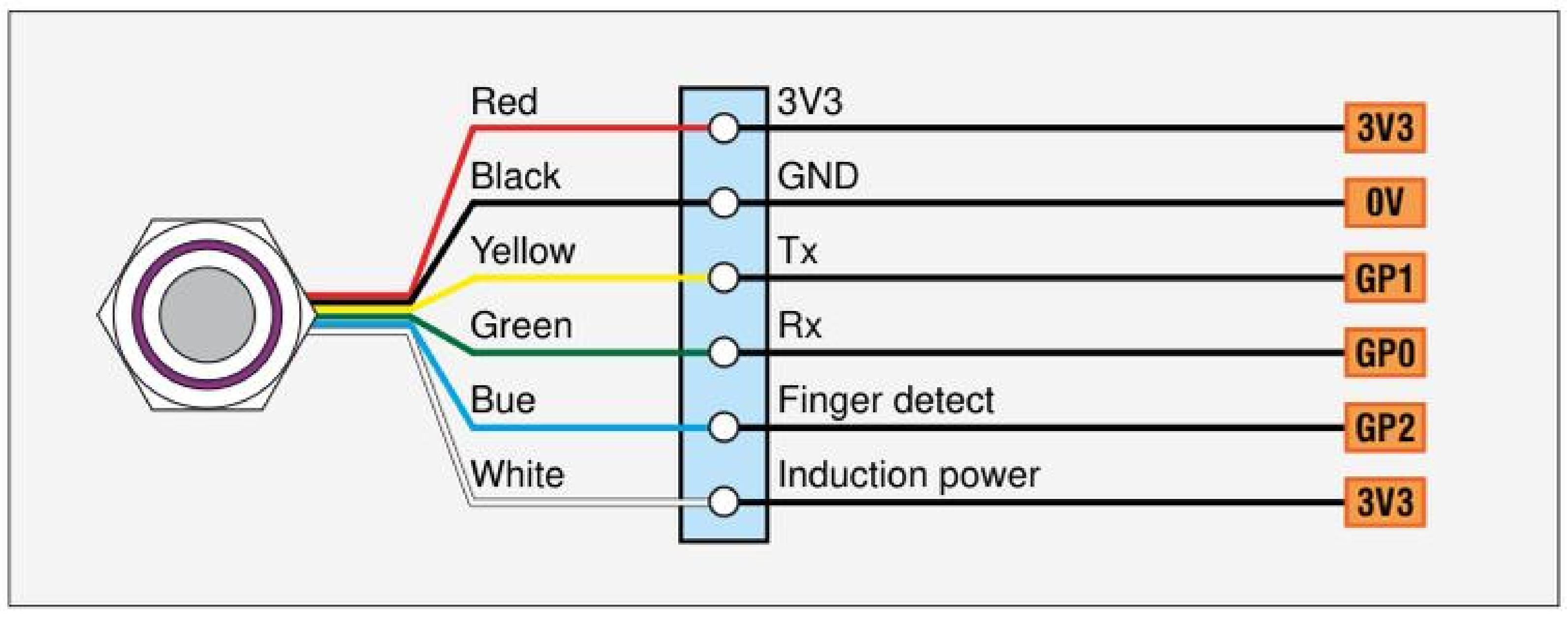

Fig.2. There are six wires coming from the back of the R503 fingerprint module. All six connections need to be made.

Connecting the module

There are six cables from the module that are terminated in a 6-pin, 1mm-pitch connector. To make it easy to connect to the PicoMite, I recommend this connector is cut off, and six short female DuPont leads are soldered in its place. All six cables need to be connected to the PicoMite, as shown in Fig.2.

The red and white cable are both connected to 3.3V, and the black cable to 0V. The serial connection is on the yellow and green cables. Yellow is the transmit (Tx) output from the module that needs to connect to a receive (Rx) COM pin on the PicoMite – here we will use GP1. Green is the receive (Rx) pin on the module that connects to a transmit (Tx) COM pin on the PicoMite (GP0 in this case).

This leaves one more connection, which is referred to in the datasheet as the 'WAKEUP' pin. However, I like to refer to it as the 'Finger Detect' pin. It is an output pin from the module that connects to an input on the PicoMite (in this case we will use GP2). When no finger is present on the sensor, the output will be at 3.3V, but when a finger is detected the output goes low. We could use this output signal from the fingerprint module to either wakeup the PicoMite via an interrupt (useful if we were to put the module and PicoMite to sleep), or we could simply monitor the state of GP2 to determine if a finger is currently on the sensor, or not (this latter method is what we will be using).

Now carefully make the six connections. Once completed, we will need to test things out. But first, let's understand the format of any message sent between the PicoMite and the R503.

Message structure

The structure of any message (to or from the fingerprint module) is best shown diagrammatically. Fig.3 shows there are always six parts to any message, as explained below.

1. HEADER – These are the first two bytes, and they need to contain the hexadecimal (hex) values of `EF` and `01` respectively. These are fixed in value and represent 'start-of-message'.

2. ADDRESS – These are the next four bytes, and by default all contain the hex value `FF`. Note that these bytes can be changed to contain a new address value, but we won't be altering this value in our application.

3. IDENTIFIER – This seventh message byte is just a single byte which identifies the type of message being sent. Four values are valid:
`01` means the message is a 'Command'. A command message is sent from the PicoMite to the module.
`02` means the message is 'Data': this message could be in either direction and always follows a `01` or `07` message.
`07` means the message is an 'Acknowledge', meaning it's a response message from the module to the PicoMite.
`08` means the message is the 'End of Data'. It can follow any of the above messages whenever sending the last chunk of data that in total is more than 255 bytes in length.

Micromite code

There is no project code this month, but where applicable, code is available for download from the PE website.

4. LENGTH – The next two bytes (byte 8 and 9) indicate the number of bytes remaining in the message; ie, the number of bytes in the next two sections ('PACKAGE DATA' and 'CHECKSUM')

5. PACKAGE DATA – This will always be at least one byte long, and can be up to a maximum of 254 bytes long (depending on which data sheet you believe!). For a Command message, it contains the specific command number (referred to as the 'instruction code' in the datasheet). It also contains any parameters relevant to the specific command.

For an Acknowledge message, it contains a response result (referred to as a 'confirmation code' in the datasheet) along with any response data. It should be under 253 bytes in length (but if there is more response data, then that is wrapped into either a 'Data' message or an 'End of Data' message). For either a 'Data' or an 'End of Data' message, it simply contains the data required to be sent.

6. CHECKSUM – These are always the last two bytes in a message and can be used for error checking. The value contained in these two bytes is the arithmetic sum of all byte values in the IDENTIFIER, LENGTH and PACKAGE DATA. Any overflow is simply ignored.

Puting the structure to work

To help make the above a little clearer, we will now work through the construction of a simple command message that is sent from the PicoMite to the fingerprint module. This example message will use the command to turn on the blue ring-LED. For completeness, we will also look at how to interpret the response (the 'Acknowledge' message) that is sent back to the PicoMite. Note that an Acknowledge message from the fingerprint module will only be sent after receiving a correct Command message. If the Command message contains an incorrect Checksum value, then no Acknowledge will be sent.

Constructing a Command message

Referring to Fig.3, we will now look at the six sections of the command message to turn on the blue ring-LED. The critical section is the PACKAGE DATA, which contains the actual command number, plus any associated parameters.

According to the datasheet, the command to control the ring-LED is 'Aura Control', or more specifically 'AuraLedConfig'. The command number (ie, instruction code) is the hex value **`35`**. It has four parameters that are associated with this command; these are as follows (taken from the datasheet):
1. Control Code – the LED mode: Breath (`01`), Flash (`02`), On (**`03`**), Off (`04`), Fade-On (`05`), Fade-Off (`06`)
2. Speed (**00**-FF) **–** the speed applied to either the Breath, Flash, Fade-On, or Fade-Off function
3. Colour Index – the colour of the ring-LED: Red (`01`), Blue (**`02`**), Purple (`03`)
4. Times – the number of cycles: **`00`** = infinite, otherwise `01–FF`. Applies only to Breath or Flash modes

Now that we know the above values, let's construct the Command message:

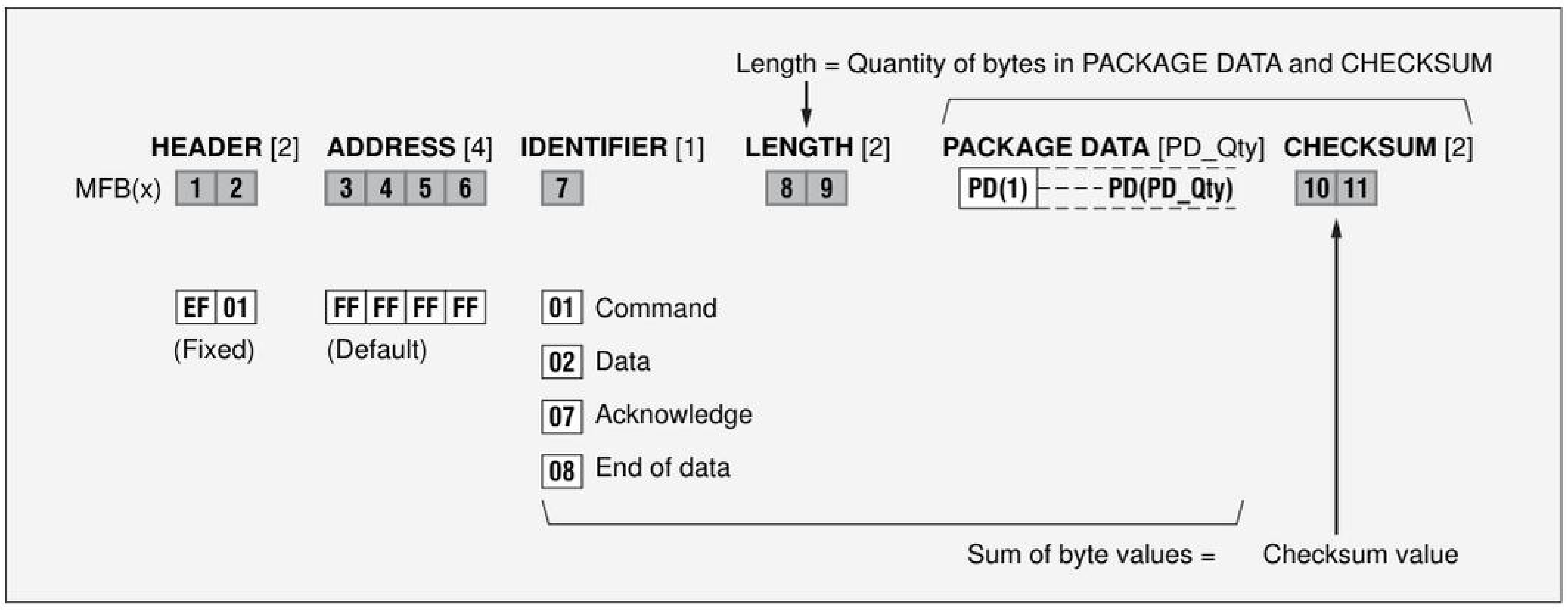

Fig.3. The structure of the message contains six elements as shown here. See text for full details of how the contents are calculated and interpreted. Note that all byte values are shown as a hexadecimal number.

`HEADER = EF 01` (fixed value)
`ADDRESS = FF FF FF FF` (default value)
`IDENTIFIER = 01` (a Command message)
`LENGTH = 07` (5-bytes in Package-Data plus 2-bytes in Checksum)
`PACKAGE DATA = 35 03 00 02 00` (from the above explanation where values are highlighted in bold)
`CHECKSUM = 00 42` (sum of byte values 01 + 07 + 35 + 03 + 00 + 02 + 00 (in hex))

Interpreting the Acknowledge response

Referring to the datasheet, you will see that the PACKAGE DATA in the Acknowledge response simply contains a single byte which is the confirmation-code. The value of this is either **00** (for success), or 01 (for failure). So, the response message we expect to see back is as follows:

`HEADER = EF 01` (fixed value)
`ADDRESS = FF FF FF FF` (default value)
`IDENTIFIER = 07` (an Acknowledge message)
`LENGTH = 03` (1 byte in Package Data plus 2 bytes in Checksum)
`PACKAGE DATA = 00` (if successful)
`CHECKSUM = 00 0A` (sum of byte values 07 + 03 + 00 (in hex))

Note that if an error occurred, the Package Data would contain the value `01`, and the Checksum would contain `00 0B`.

Message demo

Now that we have seen how to construct the bytes for a message that is sent to the fingerprint module, and also understood what the response should look like, let's now send the actual Command message to see if it does indeed turn on the blue ring-LED as we expect. We will also check the values returned in the Acknowledge response message. Performing this simple test will also check that we have connected the fingerprint module correctly.

Download the file **FP_MessageDemo1.txt** from the December 2022 page of the *PE* website and install the program into the PicoMite. When you `RUN` the program you should see the blue ring-LED turn on. If not, check the six connections. A common error with serial devices is getting the Tx and Rx connections reversed – remember, Tx from the fingerprint reader goes to Rx on the PicoMite, and Tx from the PicoMite goes to Rx on the fingerprint module.

Challenge

If you examine the program code, you will see that it is well commented, allowing you to try other parameter values to make the LED behave differently. Why not make it flash a different colour, and then change the speed of the flashing. Also, try other parameter settings.

Note that you do not need to calculate the two-byte CHECKSUM values as these are calculated automatically by the program. All you need to do is set the value for `PD_Qty` to the number of bytes being sent in the PACKAGE DATA, and then set these values in the `TxPD()` array, starting with the first byte in `TxPD(1)`. The two-byte LENGTH values are also calculated for you, making this program very easy to use.

Once you have mastered controlling the LED, have a look at some other commands from the datasheet. There is even a random number generator (`GetRandomCode` which is instruction code `14` (hex))

Next time

Now that we have a working fingerprint module that we know how to control, in *Part 2* we will look at the commands that are used to perform a fingerprint enrolment, and also the commands to perform a search of stored fingerprint templates. We will conclude with software for a standalone PicoMite fingerprint reader that brings everything together.

Until then, stay safe, and have FUN!

Questions? Please email Phil at:
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Max's Cool Beans

By Max the Magnificent

Flashing LEDs and other engineering temptations – Part 34

In my previous column (PE, November 2022), I waxed eloquently on the topic of rotary encoders. Following this, I received an email from *PE* community member Iain Sharp who hails from Nottingham, which is where my dad was raised. Iain tells me that his day-job involves supporting the development of some very cutting-edge technology, but that his role these days is mostly focused on project management and budget issues, so he spends his spare time doing interesting (and diverse) hands-on projects that remind him why he got into engineering in the first place.

Rotate that!

One such example is Cyclepong (do see this: **https://bit.ly/3RYRQG8**), which is an update of the classic arcade game Pong (**https://en.wikipedia.org/wiki/Pong**) using bikes as the controllers. Billed as 'Bringing two of humanities greatest inventions together,' Cyclepong (Fig.1) also promises to 'Build thighs of steel (weather permitting).' At the time of this writing, Cyclepong is on show at Novelty Automation in London (**https://bit.ly/3Vo8Vfw**). Iain's current project is an electromechanical version of the classic Lunar Lander computer game (**https://bit.ly/3ESSnX4**), but we digress...

In his email, Iain spake as follows: 'Hi Max, Re your piece in *PE* Nov 22 on the work you and Joe Farr are doing with quadrature encoders. There is a 'trick' to decoding them that used to be well known but seems to have been largely forgotten more recently. Instead of tracking the state of the encoder and determining which signal is 'leading' to work out the direction of rotation, you can find the direction from the signal state when a signal transition takes place. For example, looking at Fig.4 in your piece. If A goes from Low->High when B is low then this is always a CW step. If A goes from Low->High when B is high this is always an ACW step. You can build a truth table for all the possible combinations (as you would expect it's very symmetrical) and immediately know the direction of rotation from the direction of the transition and the state of the other signal. In fact, if you don't need to read the encoder at full resolution you can make things even simpler. I suspect this is why some of the encoders you looked at give two or four transitions per click. If you only need quarter resolution for example, you can just look for Low->High transitions of signal A and use signal B to tell you the rotation direction. This type of approach is simple to implement and doesn't need any information about the previous state of the encoder or where the 'click' points are. I use this approach in Cyclepong.'

Unfortunately, as I pen these words, everything feels a little 'fluffy around the edges' on the cognitive processing front. I just got back from a visit to my doctor who tells me I tested positive for Covid. I can't believe it, I had it only three months ago, I'm too young for all this excitement. They've put me on antivirals (Q: 'Do you have the antivirals?' A: 'No, I always walk this way!') so I hope to return to full cognitive capacity in a few days' time, which is when I'll peruse and ponder Iain's proposal in more depth and give it the consideration it deserves. Having said this, my brain is still tick-tocking away in the background (albeit skipping the occasional tick or tock), and it's trying to decide if Iain's simplified scheme works while still addressing the problem of noisy signals caused by switch bounce. Another issue Joe and I wish to address is preventing the system

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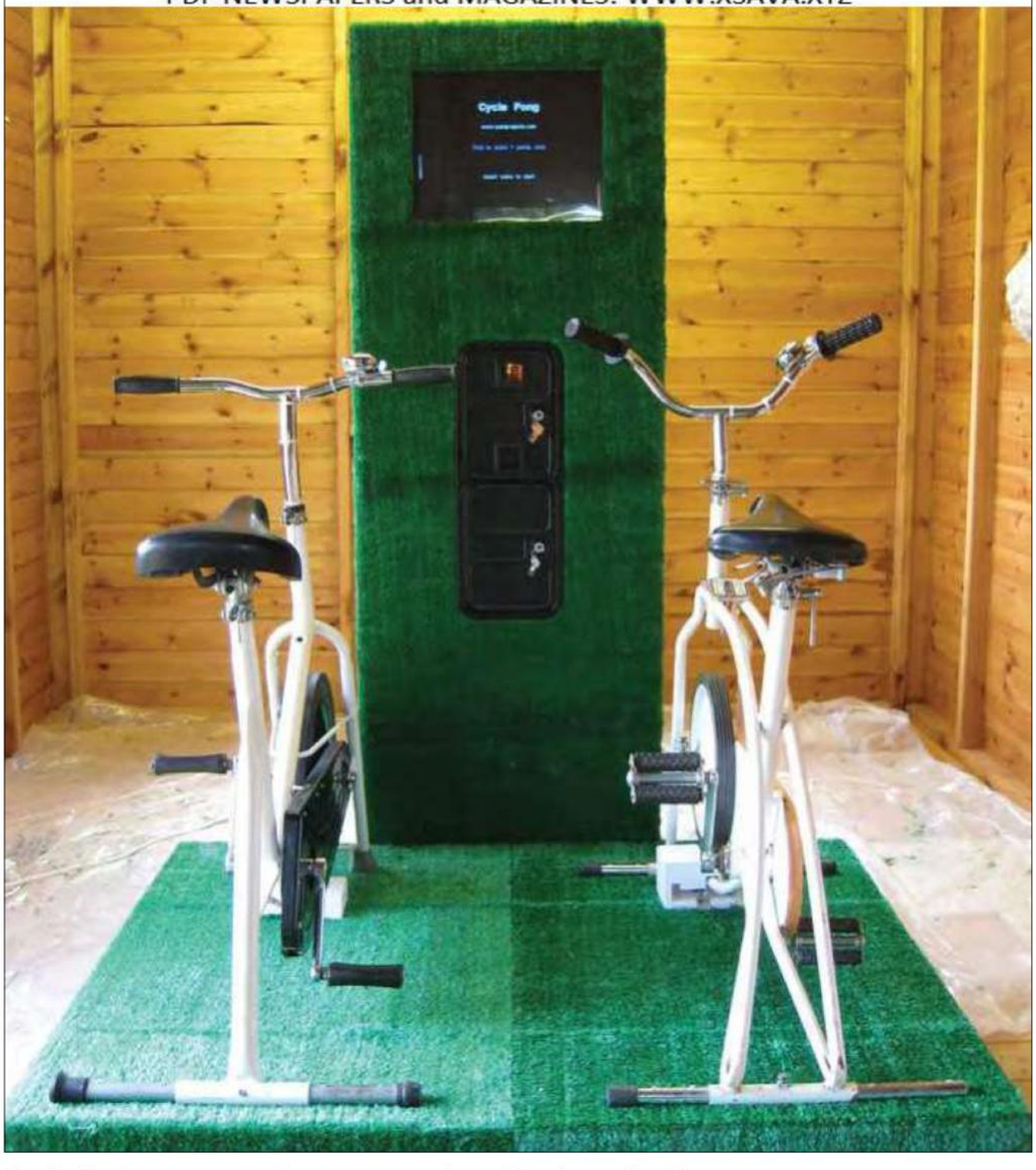


Fig.1. Cyclepong: experience man and machine in perfect harmony.

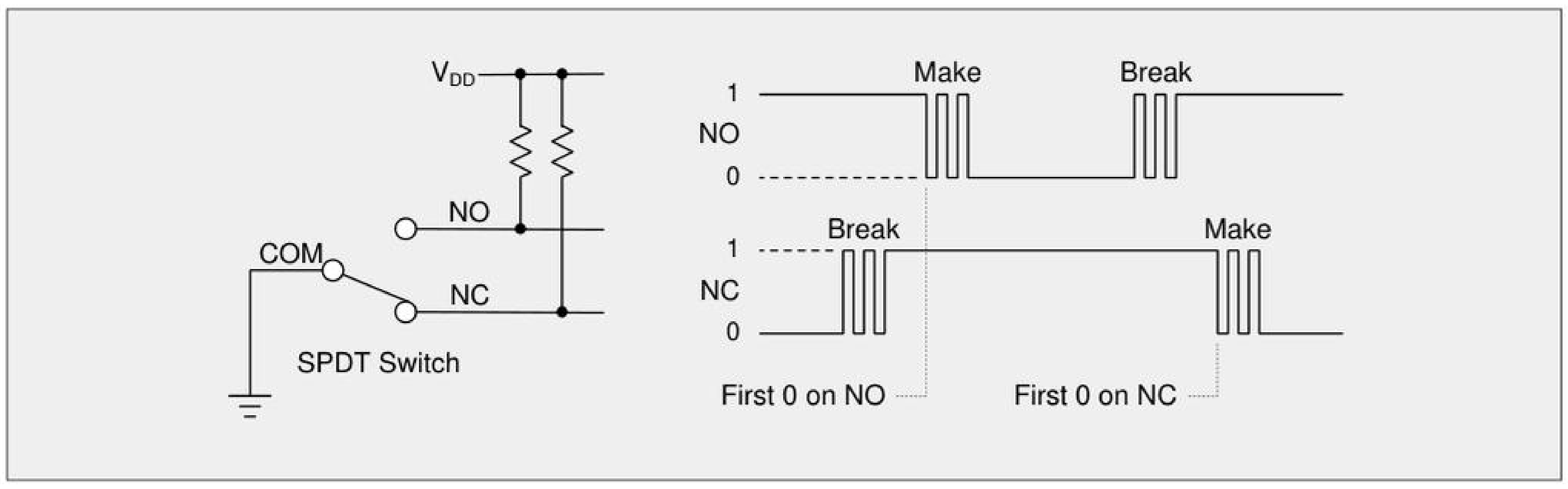


Fig.2. Switch bounce on an SPDT switch.

from getting confused when you are rotating the knob quickly and you turn it halfway past the final 'click' and then return it to the final 'click' location. This will also require some pondering in the context of Iain's suggestions.

A tight squeeze

Speaking of switch bounce... were you by any chance wondering how I spent last Saturday? You were! Well, this is your lucky day because I'm in the mood to share. In previous columns, we've talked about the problem with switch bounce for single-pole, single-throw (SPST) switches (*PE*, March 2022) and single-pole, double-throw (SPDT) switches (*PE*, April 2022). It's the bounce on the latter type which interests us here (Fig.2). Remember that NO stands for 'normally open' and NC stands for 'normally closed.'

The last time we talked about this, we looked at how to remove this bounce using two back-to-back NAND gates. For the purpose of these discussions, we are focused on the small breakout board (BOB) that LogiSwitch uses to debounce SPDT microswitches and small push-button switches (Fig.3a). This board is 0.45-inch wide and 0.5-inch tall. On the top side, there's a small LogiSwitch IC, a capacitor, and (in the lower middle of the board) a field-effect transistor (FET), which protects you if you apply the voltage the wrong way round. On the bottom of the board are three large pads. From top to bottom (in this image) they are GND, NO (fed from the switch's normally open terminal), and NC (fed from the switch's normally closed terminal).

The five small pads on the edge of the BOB are V+, NH (normally high), NL/HS (normally low with handshake), TG (toggle) and GND. When the switch is in its inactive state, the NH output from the BOB is high (logic 1). When the switch is activated (which we take to be the first 0 on NO), the NH signal goes low (logic 0). When the switch is deactivated (which we take to be the first 0 on NC), the NH signal returns to its high state.

The NL/HS signal presents the opposite values to the NH signal with an added twist. When the switch is activated and

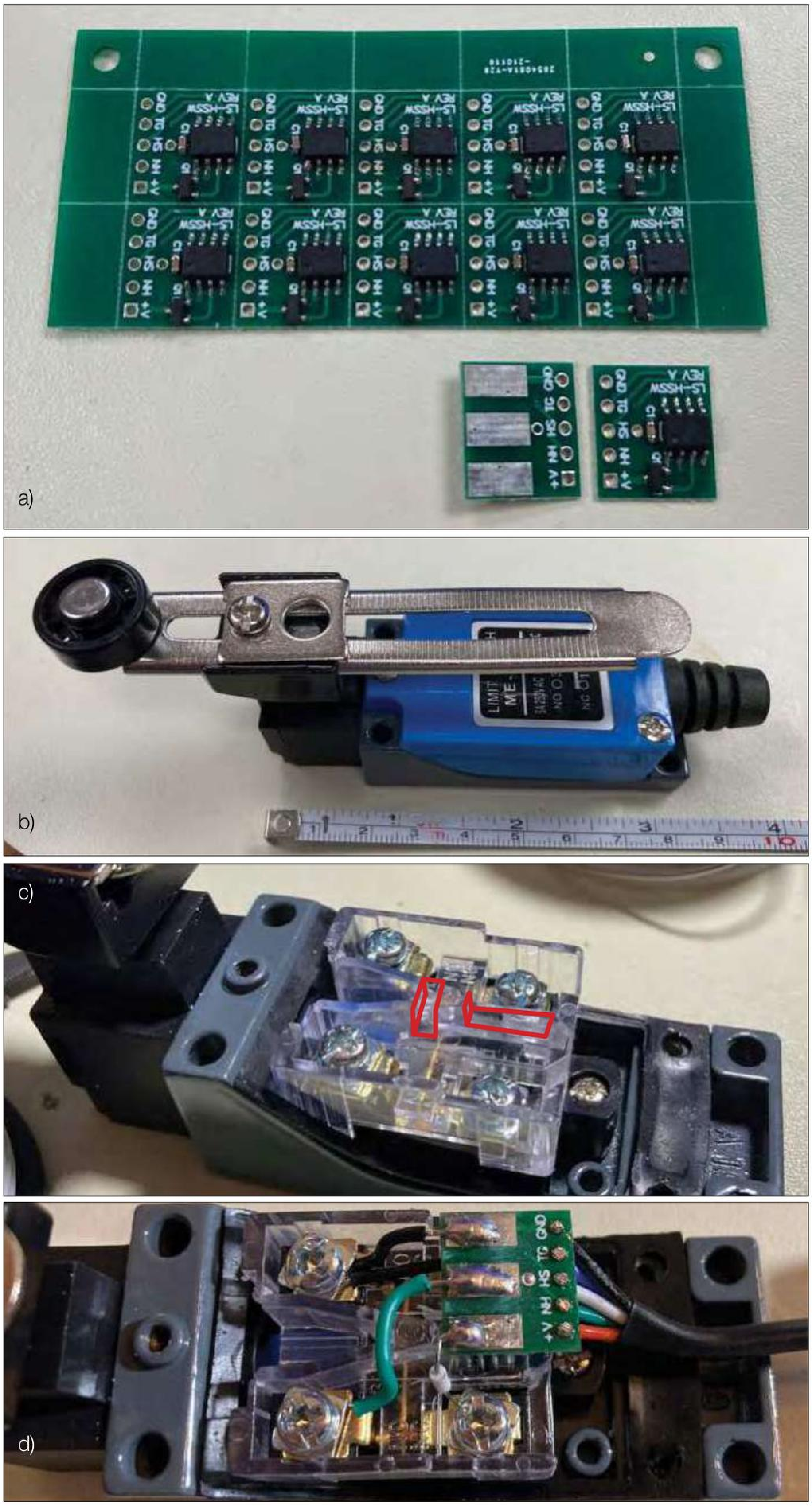


Fig.3. Inserting a BOB into a very small space. Top to bottom: a) LogiSwitch breakout boards (BOBs) used to debounce SPDT microswitches and small pushbutton switches; b) 8108 lever-arm limit switch with adjustable roller – my target for the LogiSwitch BOB; c) There's not a lot of spare space inside the limit switch. I had to file down some plastic to make everything fit (the surfaces marked red); and d) connecting it all up.

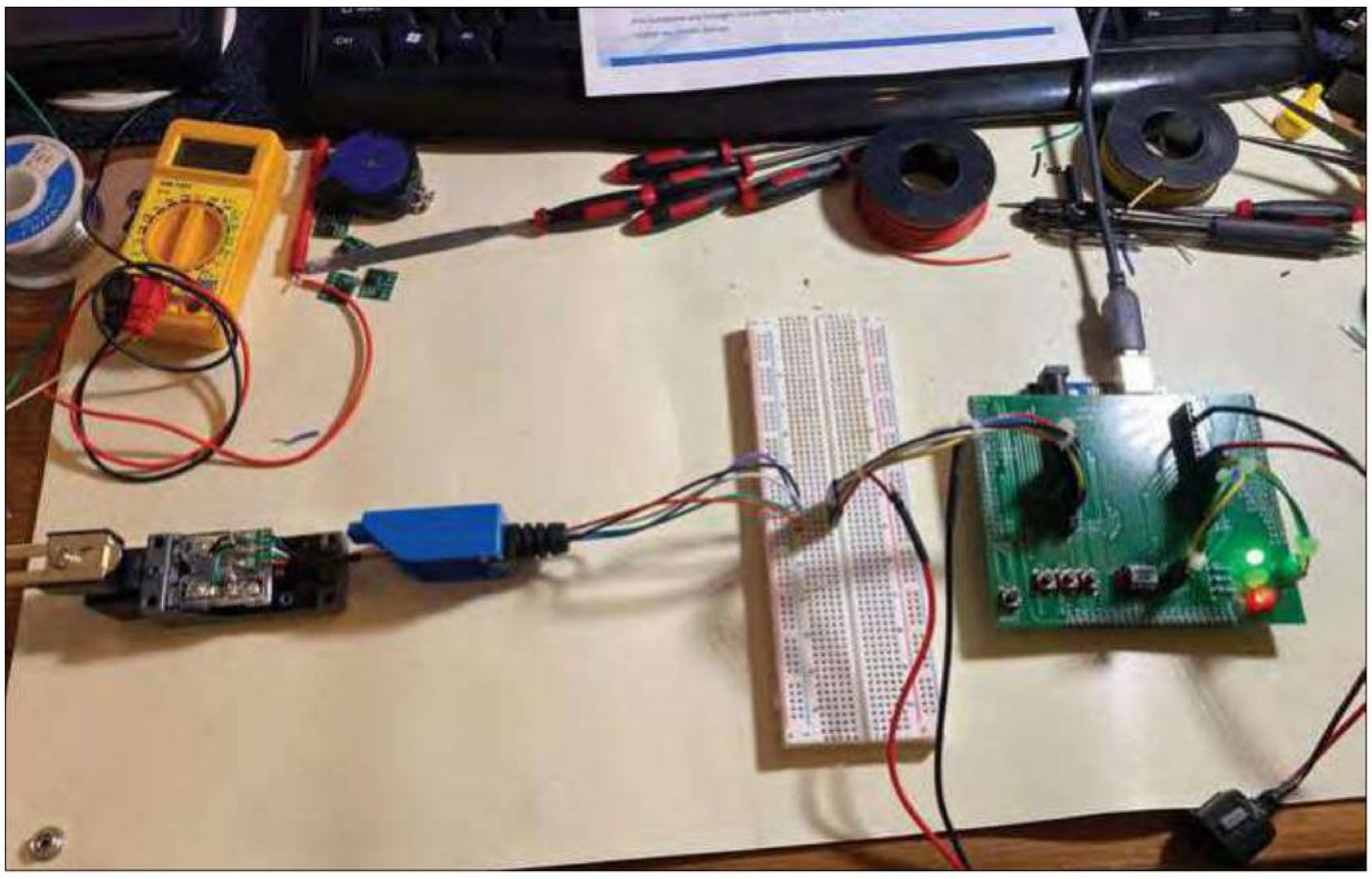


Fig.4 Checking the LogiSwitch BOB works in the limit switch.

the NL/HS signal goes high, the program in the microcontroller that's monitoring and using this signal can change its input to an output, pull the signal low for 5µs, and then return it to being an input again. The LogiSwitch IC will understand this to be an acknowledgement that the switch event has been seen and it will take over pulling this signal low. This saves you having to set a flag in your code to say when you are waiting for the switch to go inactive. Last, but not least, the TG signal starts off in a high state. Every time the switch is activated, the TG signal toggles to its opposite state.

My mission was to insert this BOB into an 8108 lever-arm limit switch with adjustable roller (Fig.3b). These are wonderful devices, but it has to be acknowledged that there's not a lot of spare space inside (Fig.3c). What is inside is four individual terminals. The two on the left-hand side of this image are marked 'NO', while the two on the right are marked 'NC'. When the switch is in its deactivated state, a small bar connects the two NC terminals. When the switch is activated, this bar moves, disconnecting the two NC terminals and connecting the two NO terminals.

Observe the clear plastic piece that holds everything in place. The blue outer shell sits on top of this without any gap whatsoever. I started by covering the internals with painter's masking tape to stop dust getting anywhere it shouldn't. I then used a small file to make a wire-sized groove between the two halves of the clear plastic (the red lines shown on the left). There are 'steps' in the clear plastic on the right (on the far side, middle, and nearside pieces sticking out). I also filed half of the middle step down further to make room for the FET on that side of the BOB (the red lines shown on the right).

Next, I connected the NC and NO terminals on the far side of the switch together to give me a common (COM) signal and connected this to the GND pad on the BOB. I also connected the NC and NO terminals on the nearside of the switch to the corresponding pads on the BOB (Fig.3d).

Finally, I ran a little program on an Arduino Uno to make sure everything worked as expected before sealing the switch up again (Fig.4). Oh, did I forget to mention that I then had to do all of this for another 14 switches (sob).

Eek! Zeke!

One of the things I've been meaning to talk to you about is an amazing 11-year-old kid called Zeke. I was first introduced to Zeke and his dad Eric a couple of months ago (Fig.5). In this image we see them holding a circuit board Zeke designed using AWR Microwave Office software from Cadence Design Systems (Zeke is the one on the left).

There's so much to tell here but (as always) so little time to tell it. In a crunchy nutshell, Zeke has been interested in science and technology since he was about one and a half years old when Eric took a piece of wood and attached a small incandescent light bulb, a battery holder, and a knife switch of the type favored by Igor and Frankenstein ('It's alive! It's alive!'). Zeke carried that little creation around with him everywhere, turning it on and off and chanting 'switch, battery, light bulb… switch, battery, light bulb…'

When he was eight, Zeke informed his parents that he wanted to communicate with the astronauts and cosmonauts on the international space station (ISS). If I'd said this to my dad, he would have patted me on the head and wished me

Left-right: Fig.5. Budding electronic engineer Zeke, with his dad Eric, showing a PCB he designed; Fig.6. Zeke with his first ham radio; and Fig.7. Zeke working on his 10-foot helical antenna.

luck. By comparison, Eric told Zeke that in order to do this he would have to a) get his ham radio license and b) have a suitable radio system.

Just to make sure we're all tap-dancing to the same skirl of the bagpipes, the term 'ham radio' (a.k.a. amateur radio) refers to the use of the radio frequency spectrum for the purposes of non-commercial exchange of messages, wireless experimentation, self-training, private recreation, radio sport, contesting and emergency communications.

Thus, a few weeks later, Zeke, Eric, and Zeke's grandfather Mark attended a ham radio class together, following which they took their ham Technician exam. Eric and Mark passed first time, but Zeke failed. It took Zeke a couple of months studying and two more tries before he also got his Technician license (he now has his General license) and his own KJ7NLL call sign, at which point his grandmother, 'Bobbi,' presented him with his first ham radio (Fig.6).

Eric told me that the very first time Zeke used his radio, someone immediately responded to his young voice saying, 'Who is this and whose radio and call sign are you using?' Eric says that Zeke firmly responded, 'This is *my* radio and *my* call sign!'

The funny things is that when Zeke is talking to me, it's obvious that he's worried about leaving me behind, so every time he drops an engineering acronym like SSB into the conversation, he will pause and then say, 'that stands for single-sideband' (I feel so old).

After looking into several different techniques (one of his back-burner projects is to create his own phased array antenna), Zeke opted to build a 10-foot-long helical antenna (Fig.7). Not shown here is the chicken wire reflector Zeke has attached to one end of the antenna. This results in the bulk of the radiation coming out of the other end, thereby significantly boosting the range of the antenna.

Via the ham network, Zeke acquired two large rotors to control the azimuth and elevation of his antenna (azimuth defines the direction to face; elevation tells you how high up in the sky to look). Zeke is currently working with some software he picked up from someone on the internet. This software runs on his PC. You tell it what satellite (including the ISS) you want to track and if feeds you a constant stream of azimuth and elevation values. I will keep you updated as to Zeke's progress in future columns.

What's it all about?

I'm currently thinking about the 1966 British comedy-drama *Alfie* starring Michael Caine as handsome Cockney Alfred Elkins. The title song *Alfie* was sung over the film's closing credits. I now have the first line of the lyrics 'What's it all about, Alfie?' rattling around my poor old noggin.

'Why is that?' You ask. I shall elucidate and explicate (don't worry, I'm a professional). I recently received a letter from a distraught mother saying that her 6-year-old son, Alfie, told her that he wanted a pack of nanobots for Christmas. After explaining what nanobots are, he told her that he could put them in a barrel, add some chemicals, stir things up, and then sit back and wait for them to build him a supercomputer.

When his mom told Alfie that this was beyond the bounds of today's technology, he pointed to the relevant portion of my book, *Bebop to the Boolean Boogie: An unconventional Guide to Electronics* (**https://amzn.to/3s15Nc6**), which she had bought for him a few weeks earlier. Unfortunately, young Alfie had missed the part where I said this type of technology was something we might expect to be talking about in the 2050 edition of the book.

Alfie's mom asked if I had any suggestions to keep his mind occupied. I suggested that he read *The Chronicles of Narnia* and the *Magic Treehouse* books, both of which I think are great for kids of all ages. She replied that Alfie's 4-year-old brother Eddie loved reading those books, but that Alfie himself would rather be reading about things like logic gates, p-type and n-type silicon and field-effect transistors. She also said, 'I told him once that most grownups prefer to read stories for fun, not textbooks, and he looked at me with incredible skepticism, bordering on full disbelief.'

Fortunately, I still had a couple of tricks up my sleeves. A couple of years ago, two former teachers, Paul and Alyssa Boswell, created an awesome marble-powered computer called the *Turing Tumble* (**https://bit.ly/3TdIPKY**). They launched it as a Kickstarter project, and it went gangbusters. This comes with lots of puzzles that I'm sure will keep Alfie busy (I have one here in my office and it certainly keeps me occupied). The second, even more awesome, thing is the latest and greatest offering from Paul and Alyssa – a mechanical implementation of electronic components and systems called *Spintronics* (**https://bit.ly/3s0IoHW**). The first production run is currently on the high seas heading our way (they discovered a problem with the mechanical resistors if they were transported via airplane (the lower atmospheric pressure caused the silicone gel to leak out).

Suffice it to say that hearing about these two offerings made Alfie's long-suffering mother very happy indeed.

Open circuits

I'm really bad when it comes to remembering names and faces. This problem is only exacerbated by the fact that I've spoken at so many conferences. You'd be amazed how many people email me to say something like, 'I saw your presentation at the XYZ conference in the year of the fruit bat – I was the one who asked the question about reverberating foodle valves' (or words to that effect), to which I usually reply, 'That was you?'

The reason I mention this is that I just received an email from Philip Freidin, who hails from Silicon Valley and who started off by saying, 'You probably don't remember me, but we met a few years ago at an Embedded Systems Conference (ESC) – in 2015, I think – and chatted for about an hour. I showed you OSHChip, a 32-bit ARM CPU + Bluetooth radio packaged as a 16 pin DIP.' The funny thing is that I do remember this meeting.

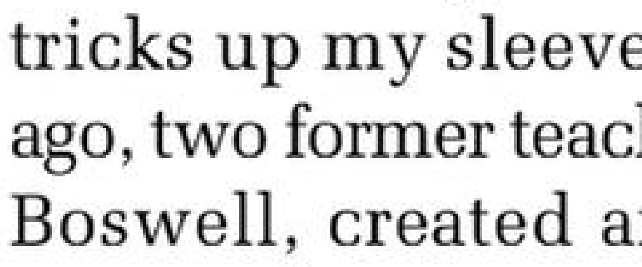
Philip went on to say, 'This email has nothing to do with any of that.' (This brought a smile to my face because it's the sort of thing I might say myself.)

It turned out that the reason for Philip's email was that two of his friends, Windell Oskay and Eric Schlaepfer, are poised to publish a book called *Open Circuits* (**https://amzn.to/3CzWZ1P**), which should hit the streets around the beginning of November 2022 (which is now as you read these words).

This book does not require any in-depth electronics knowledge and I think it will be of interest to both engineers and non-engineers alike. Basically, it contains a lot of gorgeous photographs showing the insides of electronic components. You can download a free PDF of *Chapter 1: Passive Components* from the publisher, No Starch Press (**https://bit.ly/3VyHS1i**).

I LOVE this book. My wife (Gina the Gorgeous) tells me that she never knows what to get me for Christmas. Well, safe to say that *Open Circuits* is now at the top of my wish list.

I'm afraid that's all we have time for in this column. As always, I look forward to receiving your captivating comments and insightful questions. Until next time, have a good one!



Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

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2018 Jan, Nov, Dec
2019 Jan, Feb, Apr, May, Jun

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OCTOBER 2022		
SMD Test Tweezers – PCB and pair of tweezer arms	04106211-2	11.95
SMD Test Tweezers – programmed PIC12F1572-I/SN	0410621A	7.95
Tele-com	12110211	12.95
SEPTEMBER 2022		
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Touchscreen Digital Preamp – adaptor board pair	01103192	5.95
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Multi-purpose Battery Manager – Switch Module	11104211	8.95
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Silicon Labs AM/FM/SW Radio	CSE210301C	10.95
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Bus board PCB for Analogue Vocoder	AO1-MAY22	10.95
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MARCH 2021		
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Tunable HF Preamp	CSE190502	£8.95
FEBRUARY 2021		
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PCBs for most recent *PE*/*EPE* constructional projects are available. From the July 2013 issue onwards, PCBs with eight-digit codes have silk screen overlays and, where applicable, are double-sided, have plated-through holes, and solder mask. They are similar to photos in the project articles. Earlier PCBs are likely to be more basic and may not include silk screen overlay, be single-sided, lack plated-through holes and solder mask.

Always check price and availability in the latest issue or online. A large number of older boards are listed for ordering on our website.

In most cases we do not supply kits or components for our projects. For older projects it is important to check the availability of all components before purchasing PCBs.

Back issues of articles are available – see Back Issues page for details.

Double-sided | plated-through holes | solder mask

PROJECT	CODE	PRICE
JANUARY 2021		
Nutube Valve Preamplifier	01112191	£12.95
Arduino DCC Controller	09207181	£10.95
DECEMBER 2020		
Pseudo-Random Sequence Generator	16106191	£7.95
Clever Charger	14107191	£11.95
PE Theremin Amplifier	AO-1220-01	£8.95
NOVEMBER 2020		
LED Christmas Tree (1 off)	16107181-1	£6.95
LED Christmas Tree (4 off)	16107181-2	£14.95
LED Christmas Tree (12 off)	16107181-3	£24.95
LED Christmas Tree (20 off)	16107181-4	£34.95
USB/SPI Interface Board	16107182	£5.95
45V/8A Power Supply PCB *plus* acrylic spacer	18111181	£14.95
45V/8A Power Supply front panel five-way display bezel	18111181-BZ	£3.95
Five-way LCD Panel Meter/Display	18111182	£7.95
OCTOBER 2020		
Digital Audio Millivoltmeter	04108191	£9.95
Precision Signal Amplifier	04107191	£7.95
SEPTEMBER 2020		
PE Theremin PSU	AO-0920-01	£5.95
PE Theremin PSU transformer	AO-0920-02	£7.95
Micromite Explore-28	07108191	£6.95
Ultrabrite LED Driver	16109191	£6.95
AUGUST 2020		
Micromite LCD BackPack V3	07106191	£9.95
Steering Wheel Audio Button to Infrared Adaptor	05105191	£7.95
JULY 2020		
AM/FM/CW Scanning HF/VHF RF Signal Generator	04106191	£13.95
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PE Mini-organ selected parts	AO-0720-02	£8.95
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JUNE 2020		
Arduino breakout board – 3.5-inch LCD Display	24111181	£6.95
Six-input Audio Selector main board	01110191	£10.95
Six-input Audio Selector switch panel board	01110192	
MAY 2020		
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APRIL 2020		
Flip-dot Display black coil board	19111181	£14.95
Flip-dot Display black pixels	19111182	
Flip-dot Display black frame	19111183	
Flip-dot Display green driver board	19111184	
MARCH 2020		
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DSP Active Crossover (LCD)	01106196	
JANUARY 2020		
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DECEMBER 2019		
Extremely Sensitive Magnetometer	04101011	£16.75
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NOVEMBER 2019		
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AUGUST 2019		
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PE Theremin (three boards: pitch, volume, VCA)	PETX0819	£19.50
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JULY 2019		
Full-wave 10A Universal Motor Speed Controller	10102181	£12.90
Recurring Event Reminder	19107181	£8.00
Temperature Switch Mk2	05105181	£10.45
JUNE 2019		
Arduino-based LC Meter	04106181	£8.00
USB Flexitimer	19106181	£10.45
MAY 2019		
2× 12V Battery Balancer	14106181	£5.95
Deluxe Frequency Switch	05104181	£10.45
USB Port Protector	07105181	£5.95
APRIL 2019		
Heater Controller	10104181	£14.00
MARCH 2019		
10-LED Bargraph Main Board	04101181	£11.25
+Processing Board	04101182	£8.60
FEBRUARY 2019		
1.5kW Induction Motor Speed Controller	10105122	£24.95
NOVEMBER 2018		
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JULY 2018		
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JUNE 2018		
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MAY 2018		
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MARCH 2018		
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SC200 Amplifier Module – Power Supply	01109111	£16.45
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+ Control Board	11112161	£11.95
+ Power Board	11112162	£15.30
JANUARY 2018		
High-Power DC Motor Speed Controller – Part 1	11112161	£15.30
Build the SC200 Amplifier Module	01108161	£13.95
DECEMBER 2017		
Precision Voltage and Current Reference – Part 2	04110161	£14.95
NOVEMBER 2017		
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Micropower LED Flasher (45 × 47mm)	16109161	£7.95
(36 × 13mm)	16109162	£5.95
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APRIL 2017		
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Arduino Multifunctional 24-bit Measuring Shield	04116011	£12.95
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Battery Pack Cell Balancer	11111151	£8.95
MARCH 2017		
Speech Timer for Contests & Debates	19111151	£13.45
FEBRUARY 2017		
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BY ANA4220

Next Month – in the January issue

Multi-Channel Speaker Protector

If you're driving a lot of speakers, you will need a matching compact speaker protector to prevent driver destruction, should something go wrong! Our Speaker Protector, when combined with our Hummingbird Amplifier module, is excellent when driving stereo loudspeakers with an active crossover or for surround sound systems.

Geekcreit's 35MHz-4.4GHz Signal Generator

This self-contained module is based on the Analog Devices ADF4351 wideband digital synthesiser chip. It has an onboard microcontroller unit, OLED display and pushbuttons to set the desired frequency and adjust the output level. All it needs is a 5V DC power supply.

Classic LED Metronomes

Next month, we have two Metronome designs that simulate the classic mechanical, inverted-pendulum metronome with its baton-like pointer swinging left-and-right, producing a click at each extreme. Both designs use only discrete components and simple logic chips, making them easy to understand and build.

Remote Control Range Extender

Convert an IR remote to use UHF instead, and it will work at much longer ranges. It will even work when something is between the remote and the device, regardless of where the remote is pointed!

PLUS!

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- **no power cables required as it is battery powered and can operate hours on a fully charged battery**
- **no interface cables required as it uses WiFi to connect to the computer**

Automotive Test Scope ATS605004D-XMS Key specifications

- 14 bit (0.006 %) resolution (16 bit enhanced resolution)
- Up to 500 MSa/s sampling
- 250 MHz bandwidth
- Up to 100 MSa/s continuous streaming
- Up to 256 Mpoints memory per channel
- 0.25 % DC vertical accuracy, 0.1 % typical
- 1 ppm time base accuracy

CH1
CH2
CH3
CH4

Automotive Test Scope ATS605004D-XMS*

This is just a small selection of Oscilloscopes, see www.itp101.com for more details and products

*Prices vary depending on model and specification

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